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16. ABSTRACT The report gives results of a field evaluation of the Distributed Mixing Burner (DMB) on a 98 kg/hr (215,000 lb/hr) steaming capacity, four-burner, front-wall-fired boiler. Prior to the DMB retrofit, field tests established baseline operating conditions with the pre-NSPS (New Source Performance Standards) burners originally installed in the boiler. Following DMB installation, the boiler was operated and tested with the new burners for 17 months. Under routine operation, the DMBs reduced NOx emissions by about 50%--from the baseline condition of about 0.96 to about 0.46 lb/million Btu (418 to 200 ng/J). Under carefully controlled, optimized conditions, NOx emissions were further reduced about another 20%--to about 0.3 lb/million Btu (131 ng/J). The DMB is a low-NOx pulverized-coal burner for wall-fired boiler applications. It operates under reducing conditions in the primary flame zone to minimize NOx emissions while an overall oxidizing environment is maintained in the furnace to minimize slagging and corrosion. This operation is accomplished by using air ports around the burner throat to provide staged combustion conditions at each individual burner.

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Pulverized Fuels	Distributed Mixing Burners (DMBs)	21D 21B
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Volume I - Technical Report

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TABLE OF CONTENTS

Section Page

LIST OF FIGURES. ix

LIST OF TABLES xix

1.0 INTRODUCTION 1-1
- 1.1 DMB Concept 1-3
- 1.2 Program Objectives and Approach 1-10
- 1.3 Program Chronology 1-14
- 1.4 Guide to the Report 1-19

2.0 HOST BOILER 2-1
- 2.1 Boiler Selection 2-1
  - 2.1.1 Industrial Boilers 2-2
  - 2.1.2 DMB Installation Considerations 2-15
  - 2.1.3 Host Boiler Selection Process 2-18
- 2.2 Host Boiler Characteristics 2-29
- 2.3 Boiler Baseline Evaluation 2-33
  - 2.3.1 Normal Full Load Operation 2-36
  - 2.3.2 Operating Range 2-42
  - 2.3.3 Effects of Operating Conditions on Emissions 2-46
  - 2.3.4 Low NO_x Operation 2-60

3.0 PROTOTYPE DMBs 3-1
- 3.1 Intervane Burner Tests 3-6
  - 3.1.1 Burner Design 3-6
  - 3.1.2 Test Results 3-8
  - 3.1.3 Comparison: LWS & Field Performance 3-15
- 3.2 DMB Design Criteria 3-19
  - 3.2.1 Fuel System 3-20
  - 3.2.2 Secondary Air System 3-22
  - 3.2.3 Tertiary Air System 3-25
  - 3.2.4 DMB Requirements 3-28

TABLE OF CONTENTS (Continued)

Section Page

3.3 Initial Prototype DMB 3-31
  3.3.1 Initial Prototype DMB Design 3-32
  3.3.2 Unstaged Tests of the Initial Prototype DMB in the Old and New LWS 3-41
  3.3.3 Staged Tests of the Initial Prototype DMB in the Old and New LWS 3-55
3.4 DMB with Foster Wheeler Parameters 3-60
  3.4.1 Unstaged Performance Verification 3-61
  3.4.2 Staged Performance Optimization 3-63
  3.4.3 Fuel Effects in New LWS 3-68
  3.4.4 Furnace Effects 3-71
  3.4.5 Application of the Prototype DMB with FW Parameters to WIPCO 3-74
3.5 Final Prototype DMB 3-79
  3.5.1 Final Prototype DMB Design 3-82
  3.5.2 Unstaged Performance of the Long Exit Configuration 3-85
  3.5.3 Staged Optimization of the Long Exit Configuration 3-88
  3.5.4 Optimization of Short Exit Configuration . . . 3-101
  3.5.5 Parameters Related to Field Installations 3-115
  3.5.6 Comparison of Performance with Previous Prototype DMBs 3-119
3.6 SO_2 Reduction Potential of Industrial Prototype DMBs with Sorbent Injection 3-122
  3.6.1 Sorbent Injection Tests for the DMB with Foster Wheeler Parameters 3-122
  3.6.2 Sorbent Injection with the Final DMB Configurations 3-124
3.7 Tertiary Air Port Entrainment Study 3-132
  3.7.1 Modeling Approach. 3-133
  3.7.2 Isothermal Test Results. 3-135
  3.7.3 Implications 3-143

TABLE OF CONTENTS (Continued)

Section Page

4.0 DMB FIELD EVALUATION

4.0 DMB FIELD EVALUATION 4-1
4.1 DMB Installation at Pearl Station 4-1
4.1.1 Burner Design. 4-3
4.1.2 Tertiary Air Port Locations. 4-5
4.1.3 Tertiary Air Port Design 4-9
4.1.4 Control System 4-12
4.1.5 Windbox. 4-14
4.1.6 Furnace Wall Structural Considerations 4-16
4.2 Foster Wheeler Burner Optimization Program. 4-16
4.2.1 Checkout Test Methodology. 4-19
4.2.2 Checkout Test Results. 4-20
4.2.3 Optimum Burner Configuration 4-20
4.3 DMB Optimization: Approach & Procedures. 4-32
4.3.1 DMB Field Evaluation Chronology. 4-32
4.3.2 Multi-Burner DMB Control 4-35
4.3.3 DMB Control at WIPCO 4-37
4.3.4 DMB Testing at WIPCO 4-44
4.4 Effects of Operating Parameters 4-46
4.4.1 Balancing of Burner Controls 4-46
4.4.2 Effects of Burner Stoichiometry on Emissions and Combustion Efficiency. 4-54
4.5 Minimum NO_x Emissions 4-57
4.6 Extended Staged Operation 4-68
4.6.1 Initial 30 Day Test Period 4-68
4.6.2 Second 30 Day Test Period. 4-93
4.6.3 Extended Staged tests - December, 1983 4-107
4.6.4 Final Extended Test Period 4-112
4.7 Boiler Performance. 4-124
4.7.1 Boiler Efficiency. 4-125
4.7.2 Final Steam Temperature. 4-126
4.7.3 Furnace Exit Gas Temperature 4-129

TABLE OF CONTENTS (Continued)

Section Page

4.8 Furnace Corrosion Evaluation. 4-131
4.8.1 Corrosion Panels 4-132
4.8.2 Metallurgical Analysis 4-140
4.8.3 Field Measurements of Furnace Wall Corrosion . 4-147

5.0 COMPARISON OF PROTOTYPE AND FIELD OPERATING DMBs 5-1
5.1 Emissions 5-2
5.2 Operation Characteristics 5-7

6.0 DMB APPLICATION CONSIDERATIONS 6-1
6.1 Applicability of DMB to New Utility Boiler Designs. . 6-1
6.1.1 Study Approach 6-2
6.1.2 DMB Design 6-4
6.1.3 Furnace Size 6-8
6.1.4 Firing Wall Arrangement. 6-12
6.1.5 Operation and Control. 6-23
6.1.6 Estimated Cost Impacts 6-29
6.2 Applicability of DMB Retrofits to Existing Utility Burners 6-40
6.2.1 Furnace Size 6-41
6.2.2 Physical Interferences 6-42
6.2.3 Waterside Circulation. 6-43
6.2.4 Structural Considerations. 6-44
6.2.5 Retrofit Compromises 6-44
6.3 NO_x Emission Projections. 6-51
6.3.1 Analysis of Research Furnace Data. 6-51
6.3.2 Integration of Research Furnace and Field Data 6-64

7.0 CONCLUSIONS AND RECOMMENDATIONS 7-1
7.1 Conclusions 7-1
7.2 Recommendations 7-7

8.0 REFERENCES 8-1

LIST OF FIGURES

Figure Page

1-1 Distributed Mixing Burner Concept 1-5

1-2 Distributed Mixing Burner 1-6

1-3 EPA Research, Development and Demonstration Program Involving the DMB from LIMB Capsule Report. 1-8

1-4 Program Organization. 1-13

1-5 Program Schedule. 1-15

2-1 Effect of Steam Conditions on Heat Absorption Within a Unit 2-4

2-2 Side View of Unit No. 1, a 245,000 lb/hr Utility Boiler. 2-8

2-3 Side View of Unit No. 16, a 385,000 lb/hr Utility Boiler. 2-9

2-4 Foster Wheeler NO_x Emission Correlation 2-11

2-5 Capacity and Population of Industrial and Utility Boilers 2-14

2-6 Cross-Section of Initial Industrial Boiler. 2-31

2-7 Burner Load Schedule for Initial Industrial Boiler. 2-32

2-8 Results of Particle Size Distribution Analysis. 2-38

2-9 Normal Register Adjustment. 2-40

2-10 30-Day Baseline Test Results. 2-44

2-11 Effect of Load on NO_x 2-48

2-12 Effect of Excess Air on NO_x 2-50

2-13 Effect of Load on CO. 2-51

2-14 Effect of Excess Air on CO. 2-52

2-15 Effect of Core Air Valve Setting on NO_x 2-53

2-16 Effect of Register Position on NO_x. 2-55

LIST OF FIGURES (Continued)

Figure		Page
2-17	Effect of Register and Core Air Valve Settings on CO	2-56
2-18	Particulate Test Results.	2-57
2-19	Relationship of Ash in Coal to Particulate Concentration	2-58
2-20	Comparison of Fly Ash Particle Size Distribution at 100 Percent and 70 Percent of Full Load.	2-59
2-21	Effect of Bias Firing on NO_x.	2-61
3-1	Foster Wheeler Intervane Burner	3-7
3-2	Intervane Burner Flame Shape in LWS Test Facility	3-11
3-3	Intervane Burner Data: Effect of Register Setting at Constant Load.	3-12
3-4	Intervane Burner Data: Effect of Overall Stoichiometry at Various Loads.	3-13
3-5	Intervane Burner Data: Effect of Load at Constant Primary Stoichiometry	3-14
3-6	Intervane Burner Data: Effect of Primary Stoichiometry	3-16
3-7	Intervane Burner Data: Effect of Load	3-17
3-8	Effects of Fuel System Variables on DMB Performance . . .	3-21
3-9	Effects of Secondary Air System Variables on DMB Performance	3-24
3-10	Effects of Tertiary Air System Variables on DMB Performance	3-26
3-11	Foster Wheeler Intervane Burner	3-33
3-12	DMB Meeting Design Criteria in WIPCO Windbox.	3-34
3-13	Original WIPCO Burner Arrangement	3-36
3-14	Tertiary Port Arrangement for the Initial Prototype DMB.	3-37

LIST OF FIGURES (Continued)

Figure		Page
3-15	Cross-section of Industrial Prototype Burner Based on Foster Wheeler Design, Without Tertiary Air Ports. . .	3-38
3-16	Tertiary Port Control Valve	3-40
3-17	Effect of Inner Register Position on the Unstaged Performance of the Initial Prototype DMB.	3-43
3-18	Effect of Outer Register Position on the Unstaged Performance of the Initial Prototype DMB.	3-45
3-19	Effect of Outer Sleeve Position on Unstaged Performance of the Initial Prototype.	3-46
3-20	Effect of Outer Sleeve Position on Unstaged Performance of the Initial Prototype DMB with the Inner Register at 45° Open.	3-48
3-21	Effect of Load on Unstaged Performance at the Initial Prototype DMB with Setback = 0.	3-50
3-22	Comparison of the Effect of Load on Intervane Burner and Initial Prototype DMB Unstaged Performance	3-51
3-23	Effect of Nozzle Setback on Unstaged Performance of Initial Prototype DMB.	3-53
3-24	Effect of Overall Stoichiometry at Full Load on Unstaged Performance of Intervane Burner and Initial Prototype DMB	3-54
3-25	Initial Prototype DMB Staged Performance in the Original LWS.	3-56
3-26	Comparison of Unstaged Performance of the Initial DMB in Old and New LWS Firing Utah Bituminous Coal. . . .	3-58
3-27	Comparison of Staged Performance of the Initial Prototype DMB in Old and New LWS Firing Utah Bituminous Coal.	3-59
3-28	Performance of Prototype DMB with Foster Wheeler Parameters at Optimum Configuration in new LWS Firing Indiana 2 Coal	3-65
3-29	Range of Fly Ash Carbon Content for DMB with FW Parameters at Optimum Burner Configuration in New LWS . .	3-67

LIST OF FIGURES (Continued)

Figure | | Page
3-30 Air Flowrates and Stoichiometries Over Load Range 3-69

3-31 Turndown Range of DMB with FW Parameters in the New LWS 3-70

3-32 Effect of Fuel Composition on DMB with FW Parameters Performance in New LWS. 3-72

3-33 Containment of the Flame Produced by the DMB with FW Parameters in the New LWS and MT research Furnaces . . . 3-73

3-34 Comparison of DMB with FW Parameters Performance in the New LWS and MT with Indiana Coal 3-75

3-35 Comparison of DMB with FW Parameters Performance in the New LWS and MT with Utah Coal. 3-76

3-36 Approach for Final DMB Tests in the LWS 3-81

3-37 Cross Section of Final Prototype Burner Design Without Tertiary Air Ports. 3-83

3-38 Front Wall Arrangement for Final Prototype DMB Development Tests 3-84

3-39 Effect of Inner Register Position on Unstaged Performance of the Initial Long Exit DMB Configuration 3-86

3-40 Effect of Outer Register Position on Unstaged Performance of the Initial Long Exit DMB Configuration 3-87

3-41 Effect of Core Valve Position on Unstaged Performance of the Initial Long Exit DMB Configuration 3-89

3-42 Effect of Core Air on Air Staged Performance for Initial Long Exit DMB Configuration 3-91

3-43 Effect of Inner Register on Staged Performance for Initial Long Exit DMB Configuration 3-92

3-44 Effect of Outer Register on Staged Performance for Initial Long Exit Configuration 3-93

3-45 Effect of Staging on Burner Performance for the Initial Long Exit Configuration 3-96

LIST OF FIGURES (Continued)

Figure Page

3-46 Effect of Excess Air for the Initial Long Exit Configuration 3-97

3-47 Effect Staging on Burner Performance with Long Exit and Primary Setback = 3.0 in. 3-99

3-48 Effect of Excess Air on Staged Performance with Long Exit and Primary Setback = 3.0 in 3-100

3-49 Effect of Firing Rate on Optimum Long Exit Industrial Prototype DMB Performance. 3-102

3-50 Effect of Core Position on Staged Performance for Short Exit DMB Configuration. 3-103

3-51 Effect of Inner Register Adjustment on Staged Performance for Short Exit DMB Configuration. 3-104

3-52 Effect of Outer Register Adjustment on a Staged Performance for Short Exit DMB Configuration. 3-105

3-53 Burner Performance with Short Exit (L/D=0.4) and Setback = 3.0 in. 3-107

3-54 Effect of Excess Air on Emissions with Short Exit Configuration. 3-108

3-55 Comparison of Staged Performance of the Optimum Short Exit Configuration with Utah and Indiana Coal 3-110

3-56 Comparison of Excess Air Effect on Emissions Produced by the Optimum Short Exit Configuration with Utah and Indiana Coals 3-112

3-57 Range of Fly Ash Carbon for Final Industrial Prototype DMBs at Optimum Burner Configuration. 3-113

3-58 Effect of Firing Rate on Final Industrial Prototype DMB Performance 3-114

3-59 Effect of Tertiary Port Velocity on Short Exit Configuration Performance. 3-116

3-60 Effect of Tertiary Air Bias on short Exit Burner Performance. 3-118

3-61 Comparison of Burner Performance with Previous Industrial Prototype DMBs. 3-120

LIST OF FIGURES (Continued)

Figure		Page
3-62	Comparison of Fly Ash Carbon for Prototype DMB Designs. . .	3-121
3-63	SO_2 Reduction with Injection of Vicron 45-3 for the DMB with Foster Wheeler parameters in the LWS	3-123
3-64	Sulfur Capture with vicron and the DMB with Foster Wheeler Parameters in the MT	3-125
3-65	SO_2 Capture Achieved with the Optimum Long Exit DMB Configuration.	3-126
3-66	SO_2 Capture Potential with Short Exit Configurations of Final DMB	3-128
3-67	Effect of Exit Length on SO_2 Capture with Final DMB Configurations.	3-129
3-68	Effect of Fuel Composition of SO_2 Reduction with Sorbent Injected Through the Tertiary Air Ports of the Final DMB Configuration.	3-130
3-69	Summary of SO_2 Capture Using Vicron ($CaCO_3$) Injection with Industrial Prototype DMBs.	3-131
3-70	Isothermal Flow Study - Burner Design	3-134
3-71	Isothermal Flow Study - Burner and Tertiary Air Port Arrangement.	3-136
3-72	Center Tertiary Air Jet Mixing - Balanced Burner, High Momentum Tertiary Air.	3-139
3-73	Center Tertiary Air Jet Mixing - Balanced Burners, Low Momentum Tertiary Air	3-140
3-74	Center Tertiary Air Jet Mixing - Unbalanced Burner Flow . .	3-142
4-1	Pearl Station DMB	4-4
4-2	Desired DMB Arrangement	4-6
4-3	Final Compromise Port Arrangement	4-8
4-4	Cylindrical Tertiary Port Damper Design	4-10
4-5	Tertiary Port Damper Design for Lower Ports	4-11
4-6	Front Wall Support - Front View	4-17

LIST OF FIGURES (Continued)

Figure Page

4-7 Front Wall Support - Side View. 4-18

4-8 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 3.3% O_2 for a Nozzle Setting of 4 Inches. 4-24

4-9 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 3.3% O_2 for a Nozzle Setting of 0 Inches. 4-25

4-10 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 3.3% O_2 for a Nozzle Setting of -3 Inches 4-26

4-11 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 5.5% O_2 for a Nozzle Setting of 4 Inches. 4-27

4-12 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 5.5% O_2 for a Nozzle Setting of 0 Inches. 4-28

4-13 Influence of Inner Register Position on NO_x Emissions for Various Outer Register Positions at 5.5% O_2 for a Nozzle Setting of -3 Inches 4-29

4-14 NO_x Emissions as a Function of Nozzle Position, Register Position, and Excess Air 4-30

4-15 Impacts of Imbalance in a Multi-Burner Array. 4-36

4-16 WIPCO DMB Operating Range 4-41

4-17 Tertiary Air Flowrate Distribution (at constant Velocity) . 4-43

4-18 Effect of Coal Nozzle Position on Staged Performance. . . . 4-48

4-19 Effect of Inner Register Adjustment on Staged Performance at WIPCO. 4-49

4-20 Effect of Outer Register Adjustment on Staged Performance at WIPCO. 4-50

4-21 Effect of Inner Sleeve Position on Staged Performance . . . 4-52

4-22 Effect of Outer Sleeve Position for Burners 1 and 2 on Staged Performance 4-53

LIST OF FIGURES (Continued)

Figure		Page
4-23	Effect of Core Air Valve Position on Staged Performance . .	4-55
4-24	Effect of Burner Zone Stoichiometry on Emission at WIPCO. .	4-58
4-25	Correlation of Combustion Efficiency with CO.	4-59
4-26	Tertiary Air Mixing Patterns.	4-67
4-27	Daily Averages of Gaseous Emissions During Initial 30-Day Test	4-73
4-28	NO_x Emissions at 20 MW During Initial 30-Day Test	4-75
4-29	NO_x Emissions at 14 MW During Initial 30 Day Test	4-76
4-30	NO_x Emissions at 3.6 Percent O_2 During Initial 30-Day Test	4-77
4-31	Effect of Load on NO_x Emissions During Initial 30-Day Test	4-78
4-32	CO Emissions at 14 MW During Initial 30-Day Test.	4-80
4-33	CO Emissions at 20 MW During initial 30-Day Test.	4-81
4-34	Effect of Load on CO Emissions During Initial 30-Day Test	4-82
4-35	Daily Averages of Emissions During Second 30-Day Test Period.	4-96
4-36	Effect of Excess Air on Emissions During First Twelve Days of Second 30 Day Test Period at Constant Load (20 ± 0.1 MW).	4-99
4-37	Effect of Load on NO_x Emissions During First Twelve Days of Second 30 Day Test Period.	4-100
4-38	Effect of Load on CO Emissions During First Twelve Days of Second 30-Day Test Period.	4-101
4-39	Daily Averages of Staged Operation During December 1983 . .	4-111
4-40	Daily Averages of Staged Operation During Final Test Period in 1984	4-116
4-41	Typical Corrosion Panel	4-133

LIST OF FIGURES (Continued)

Figure		Page
4-42	North Wall - Corrosion Test Panel Locations	4-134
4-43	South Wall - Corrosion Test Panel Locations	4-135
4-44	Rear Wall - Corrosion Test Panel Locations.	4-136
4-45	Corrosion Panel Photographs	4-141
4-46	Corrosion Panel Photomacrograph (Panel 1)	4-142
4-47	Corrosion Panel Photomacrograph (Panel 3)	4-143
4-48	Corrosion Panel Photomacrograph (Thickness)	4-144
4-49	Corrosion Panel Photomacrograph (Hardness).	4-145
4-50	Corrosion Panel Photomicrograph	4-146
4-51	Elevations of Furnace Tube Wall Measurements.	4-149
4-52	Change in Tube Wall Thickness, South Wall	4-151
4-53	Change in Tube Wall Thickness, North Wall	4-152
4-54	Change in Tube Wall Thickness, Rear Wall.	4-153
4-55	Change in Tube Wall Thickness, Front Wall	4-154
5-1	Comparison of Staging Effect on DMB Performance in the LWS and WIPCO.	5-4
6-1	Base 625 MW_e Conventional Boiler Design	6-3
6-2	Conventional NSPS Burner Arrangement.	6-5
6-3	DMB Burner Arrangement.	6-6
6-4	DMB Boiler Burner to Sidewall Spacing	6-11
6-5	DMB Boiler Furnace Width.	6-13
6-6	Relative Burner Throat Diameters.	6-15
6-7	DMB Boiler Burner-To-Burner Spacing	6-17
6-8	Conventional NSPS Firing Wall	6-18
6-9	DMB Firing Wall	6-19

LIST OF FIGURES (Concluded)

Figure		Page
6-10	Conventional NSPS Duct/Windbox Arrangement.	6-21
6-11	DMB Duct/Windbox Arrangement.	6-22
6-12	DMB Boiler Air Flow	6-25
6-13	DMB Boiler Burner Stoichiometry	6-26
6-14	Control Subsystem Schematic	6-28
6-15	Air Flow - DMB Unit	6-30
6-16	Operating Cost Impact Due to Carbon Losses.	6-39
6-17	Circular Tertiary Port Design	6-46
6-18	Slightly Elongated Tertiary Air Port With Division.	6-47
6-19	Elongated Tertiary Air Port Design With Division.	6-48
6-20	Elongated Shared Tertiary Air Port Design	6-49
6-21	Research DMBs	6-53
6-22	Research Furnaces	6-55
6-23	Comparison 1 Single-Secondary Development DMBs in Old LWS and SWS	6-59
6-24	Comparison 2 Initial Prototype DMB in Old and New LWS . . .	6-61
6-25	Comparison 3 - Final Prototype DMB in New LWS and MT. . . .	6-62
6-26	Comparison 4 - Versatile DMB in New SWS	6-63
6-27	Projection of Research Furnace and Field NO_x Emission Data	6-67

LIST OF TABLES

Table		Page
1-1	DMB Data Base	1-11
2-1	Boiler Design Comparison	2-5
2-2	Design Parameter Comparison	2-7
2-3	Candidate Four Burner Units	2-20
2-4	Candidate Six to Twelve Burner Units	2-21
2-5	Weighting Factor Summary	2-24
2-6	Prioritized List of Units	2-25
2-7	Initial Small Boiler Candidates	2-27
2-8	Large Boiler Candidates	2-28
2-9	Initial Industrial Boiler Field Site Characteristics	2-30
2-10	Typical Coal Fired at WIPCO's Pearl Station Unit 1	2-34
2-11	Nominal Boiler Operating Conditions and Emissions	2-37
2-12	Furnace Wall Gas Composition During the Optimization Tests	2-41
2-13	Furnace Wall Gas Composition During Effluent Stream Analysis Test	2-41
2-14	Range of Operating Conditions Achieved During the Optimization Tests Compared to the 30-Day Baseline Test	2-43
2-15	Range of Gaseous Emissions	2-47
3-1	Prototype DMB Test Summary	3-2
3-2	Combustion Test Facility Characteristics	3-4
3-3	Intervane Burner Characteristics	3-9
3-4	Distributed Mixing burner Design Parameters	3-29
3-5	Initial Prototype Burner Dimensions and Adjustments	3-42
3-6	Summary of Burner Variables on Unstaged Performance of Initial Prototype DMB Using Utah Bituminous Coal	3-49

LIST OF TABLES (Continued)

Table		Page
3-7	Test Approach for DMB With FW Parameters	3-62
3-8	Performance Summary of the Prototype DMB with FW Parameters	3-77
3-9	Summary of Optimum Conditions for the Initial Long Exit DMB Configuration	3-95
3-10	Summary of Optimum Conditions for Prototype DMB	3-109
3-11	Isothermal Modeling Test Matrix	3-138
4-1	DMB Controls at Pearl Station	4-13
4-2	Inputs Required From Existing Equipment	4-15
4-3	Data Summary	4-21
4-4	Impacts of Control Changes	4-39
4-5	Range of Burner Settings for Lowest NO_x at WIPCO	4-56
4-6	Summary of Test Conditions Which Produced NO_x Emissions Less Than 0.35 lb/10^6 Btu	4-61
4-7	Fineness Tests at WIPCO	4-64
4-8	Initial 30-Day Test Burner Settings for Two-Mill, Four-Burner Operation	4-70
4-9	30-Day Test Burner Setting for Single-Mill, Two-Burner Operation	4-71
4-10	Initial 30-Day Test Average of Gaseous Emissions	4-72
4-11	Summary of Particulate Results During Initial 30-Day Test	4-84
4-12	Comparison of Burner Zone and Total Stoichiometry During the Optimization Tests and Initial 30-Day Test	4-85
4-13	Stratification in Exhaust Duct During Initial 30-Day Test	4-85
4-14	Furnace Wall Gas Composition During Initial 30-Day Test	4-87
4-15	Carbon Utilization During Initial 30-Day Test	4-89

LIST OF TABLES (Continued)

Table		Page
4-16	Summary of Coal Analyses During Initial 30-Day Test	4-90
4-17	Coal Fineness During Initial 30-Day Test.	4-91
4-18	Nominal Boiler Operating Conditions and Emissions	4-92
4-19	Second 30-Day test Burner Settings for Two-Mill, Four-Burner Operation	4-95
4-20	Overall Average of Gaseous Emissions for Continuous Staged Operation During Second 30-Day Test Period	4-97
4-21	Carbon Utilization During Second 30-Day Test Period	4-103
4-22	Summary of Coal Composition During Second 30-Day Test Period.	4-105
4-23	Comparison of Ash Fusion Temperatures of Coal Samples From the Initial and Second 30-Day Test Periods	4-106
4-24	Initial Burner Settings for December 1983 Extended Staged Tests - Two Mill, Four Burner Operation.	4-110
4-25	Analysis of Fly Ash Samples From December 1983 Test Period.	4-113
4-26	Initial Burner Settings for Final Extended Test Period for Two-mill, Four Burner Operation.	4-114
4-27	Summary of Emission During Final Extended Test Period . . .	4-117
4-28	Range of Burner Settings from February 24 to March, 2, 1984	4-119
4-29	Range of Burner Settings From March 22 to March 27, 1984	4-120
4-30	Carbon Utilization During Second 30-Day Test Period	4-122
4-31	Select Boiler Efficiency Data	4-127
4-32	Fuel Analyses	4-128
4-33	Furnace Performance	4-130
4-34	Corrosion Rate of Test Panels	4-138
4-35	Regression Analysis of Furnace Wall Corrosion Data.	4-155

LIST OF TABLES (Concluded)

Table		Page
5-1	Comparison of Foster Wheeler Prototype DMB LWS Performance with WIPCO Boiler Requirements.	5-3
5-2	Comparison of Optimum Foster Wheeler Prototype DMB Conditions to Second Thirty Day Test Settings	5-6
5-3	Comparison of DMB Operational Characteristics in the LWS and WIPCO Pearl Station	5-8
6-1	Terminal Points	6-33
6-2	Case A DMB Cost Impacts	6-34
6-3	Case B DMB Cost Impacts	6-35
6-4	Data Base	6-52
6-5	Research Furnace Characteristics.	6-56
6-6	Conclusions From Data Comparisons	6-65

1.0 INTRODUCTION

This report presents the results of a field evaluation of low-NO_x pulverized coal burner technology for an industrial boiler application. The report is presented in three volumes. This Volume I presents the detailed technical results. Volume II includes the appendices to Volume I. Volume III is a Guideline Manual which summarizes the program results as a guide to future DMB applications.

The term NO_x refers to nitric oxide (NO) and nitrogen dioxide (NO_2) which are formed in the natural course of the combustion process. NO_x in the exhaust from most large combustion sources including pulverized coal-fired boilers is about 95 percent NO and 5 percent NO_2. NO_x is considered a pollutant for the following reasons:

1. NO_x compounds are toxic. Exposure to low NO_x concentrations can impair breathing, particularly for asthmatics and other sensitive people. The U.S. Occupational Health and Safety Administration (OSHA) has set the maximum concentration for eight-hour exposure to NO and NO_2 at 25 and 5 ppm, respectively. The U.S. ambient air quality standard for NO_2 is 0.05 ppm.

2. NO_x compounds contribute to acid rain. In the atmosphere, NO can be oxidized to NO_2 which can react with water to form nitric and nitrous acids (Braker and Mossman, 1971). These acids can cause direct damage to structures and plants and may also change the natural acid/base balance of rivers and lakes.

3. NO_x compounds are ingredients of photochemical smog. In the atmosphere, NO_x and hydrocarbons can react in the presence of sunlight to produce ozone, aerosols, peroxyacyl nitrates (PEN) and other species. This photochemical smog reduces visibility, causes damage to plants and causes a wide range of health effects in animals and humans (Rau, 1980).

NO_x emissions from coal combustion are typically higher than from combustion of liquid or gaseous fossil fuels because coal contains substantial concentrations of nitrogen compounds. During combustion, these compounds decompose to liberate HCN and NH_3 which react readily with oxygen to form NO_x. It has been estimated that up to 80 percent of the total NO_x emissions due to coal combustion in pre-NSPS burners is due to fuel nitrogen oxidation (Chen et al., 1982).

One of the most effective techniques for reducing NO_x emissions from high-nitrogen fuels is staged combustion. This involves firing the fuel under oxygen deficient conditions initially followed by secondary air addition to complete combustion. In the fuel-rich primary zone, the bound nitrogen compounds are preferentially reduced to N_2 prior to the addition of the secondary air. The effectiveness of staging in reducing NO_x emissions depends on the combustion conditions, particularly in the fuel-rich primary zone. The optimum stoichiometry is typically in the range of 70 percent theoretical air (TA). Staging has been demonstrated to be effective in reducing NO_x emissions on full-scale wall-fired boilers through the use of overfire air ports (Crawford, 1974). However, the primary zone stoichiometry must be maintained above stoichiometric conditions (100 percent TA) to avoid slagging and corrosion in the lower furnace and to achieve adequate char burnout. This limits the effectiveness of NO_x control via overfire air ports.

For the last several years, EPA has been developing a low-NO_x pulverized coal burner that achieves staging by means of air ports around a circular burner. This Distributed Mixing Burner (DMB) allows a fuel-rich primary zone with stoichiometry near the optimum range to be established in the furnace adjacent to the burner while maintaining an overall oxidizing environment further into the furnace, minimizing slagging, corrosion and char burnout problems. Several research DMBs were fabricated and tested at firing rates up to 100×10^6 Btu/hr in single and four-burner arrays in two research furnaces. The tests covered wide ranges of burner adjustments and operating conditions. Under optimum conditions NO_x emissions less than 0.15 lb/10^6 Btu were obtained (Zallen et al., 1979). This initial DMB development appeared very promising. However, direct application to field operating systems was limited by the following factors:

1. The development DMBs were research burners. They were designed to achieve the lowest possible NO_x emissions commensurate with flame stability and combustion efficiency constraints. They did not utilize commercial burner components and were not capable of long-term operation in the commercial system.

2. The DMBs were tested in research furnaces only. It is well known that the performance of pulverized coal burners depends on furnace environment. Thus, satisfactory performance in a research furnace does not necessarily ensure satisfactory field performance.

The objective of this program was to conduct a field evaluation of the performance of the DMB on a multi-burner boiler. This involved integrating the DMB concept with commercial burner components to produce a burner meeting commercial burner standards. Burner performance was verified in a large-scale test facility. Subsequently, the burner was retrofitted to a field-operating boiler and its performance was assessed. The remainder of this section discusses the DMB concept, its development history, and the organization and chronology of the program. The technical details are discussed in the remainder of this report.

1.1 DMB Concept

The DMB concept involves staging the combustion process to minimize NO_x emissions while maintaining an overall oxidizing atmosphere in the furnace to minimize slagging and corrosion. NO_x production from fuel nitrogen compounds is minimized by driving a majority of the compounds into the gas phase under fuel-rich conditions and providing a stoichiometry/temperature history which maximizes the decay of the evolved nitrogen compounds to N_2. Thermal NO_x production is minimized by heat loss from the fuel-rich zone which reduces peak temperatures.

A schematic representation illustrating how the DMB design stages the fuel/air mixing sequentially is shown in Figure 1-1. The combustion process occurs in three zones. In the first zone pulverized coal transported by the primary air combines with the inner secondary air to form a very fuel-rich (30 to 50 percent theoretical air) recirculation zone which provides flame stability. The coal devolatizes and fuel nitrogen compounds are released to the gas phase. Outer secondary air is added in the second "burner zone" where the stoichiometry increase up to about 70 percent theoretical air. This is the optimum range for reduction of bound nitrogen compounds to N_2. Air to complete the combustion processes is supplied through tertiary ports located outside the burner throat. This allows substantial residence time in the burner zone for decay of bound nitrogen compounds to N_2 and radiative heat transfer to reduce peak temperatures. The tertiary ports surround the burner throat providing an overall oxidizing atmosphere and minimize interactions between adjacent burners.

Figure 1-2 shows the installation of a typical DMB in a wall-fired boiler. The DMB design components illustrated are:

- Four independently controlled airstream systems divide the total combustion air into:
    1. A central airstream used for ignition during startup and cooling during normal operation (Stream A).
    2. The primary airstream carrying the coal (Stream B).
    3. Two concentric secondary airstreams to provide inner and outer secondary airflow (Streams C and D, respectively).
    4. Four outboard tertiary air ports (Stream E).
- An annular fuel injector which produces a uniform annular coal distribution.

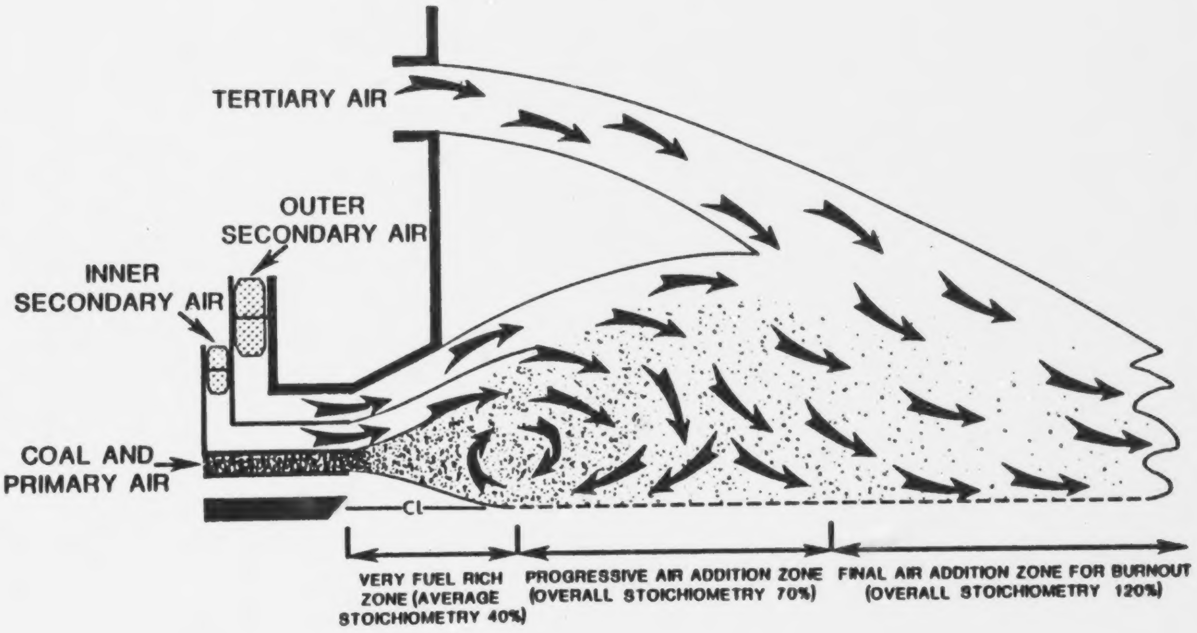
TERTIARY AIR
OUTER SECONDARY AIR
INNER SECONDARY AIR
COAL AND PRIMARY AIR
CL
VERY FUEL RICH ZONE (AVERAGE STOICHIOMETRY 40%)
PROGRESSIVE AIR ADDITION ZONE (OVERALL STOICHIOMETRY 70%)
FINAL AIR ADDITION ZONE FOR BURNOUT (OVERALL STOICHIOMETRY 120%)

Figure 1-1. Distributed mixing burner concept.

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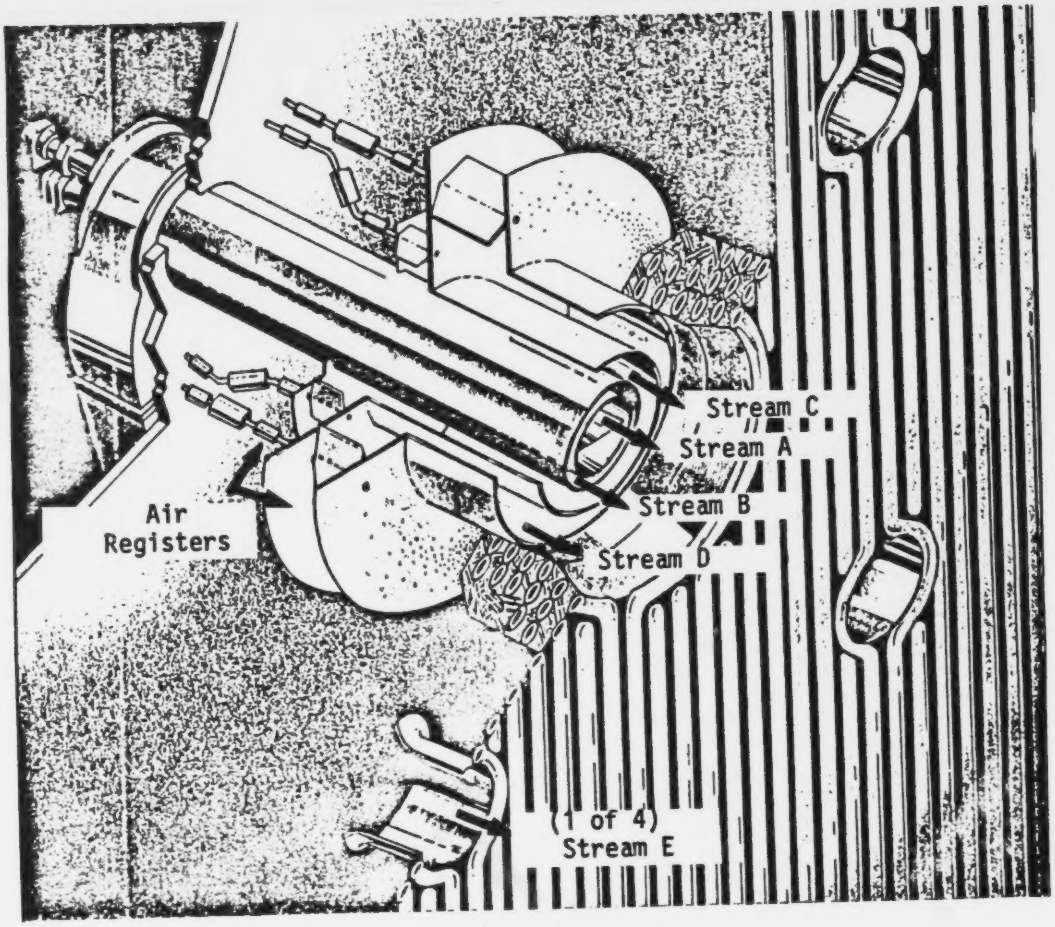

Stream C
Stream A
Stream B
Stream D
Air
Registers
(1 of 4)
Stream E

Figure 1-2. Distributed mixing burner.

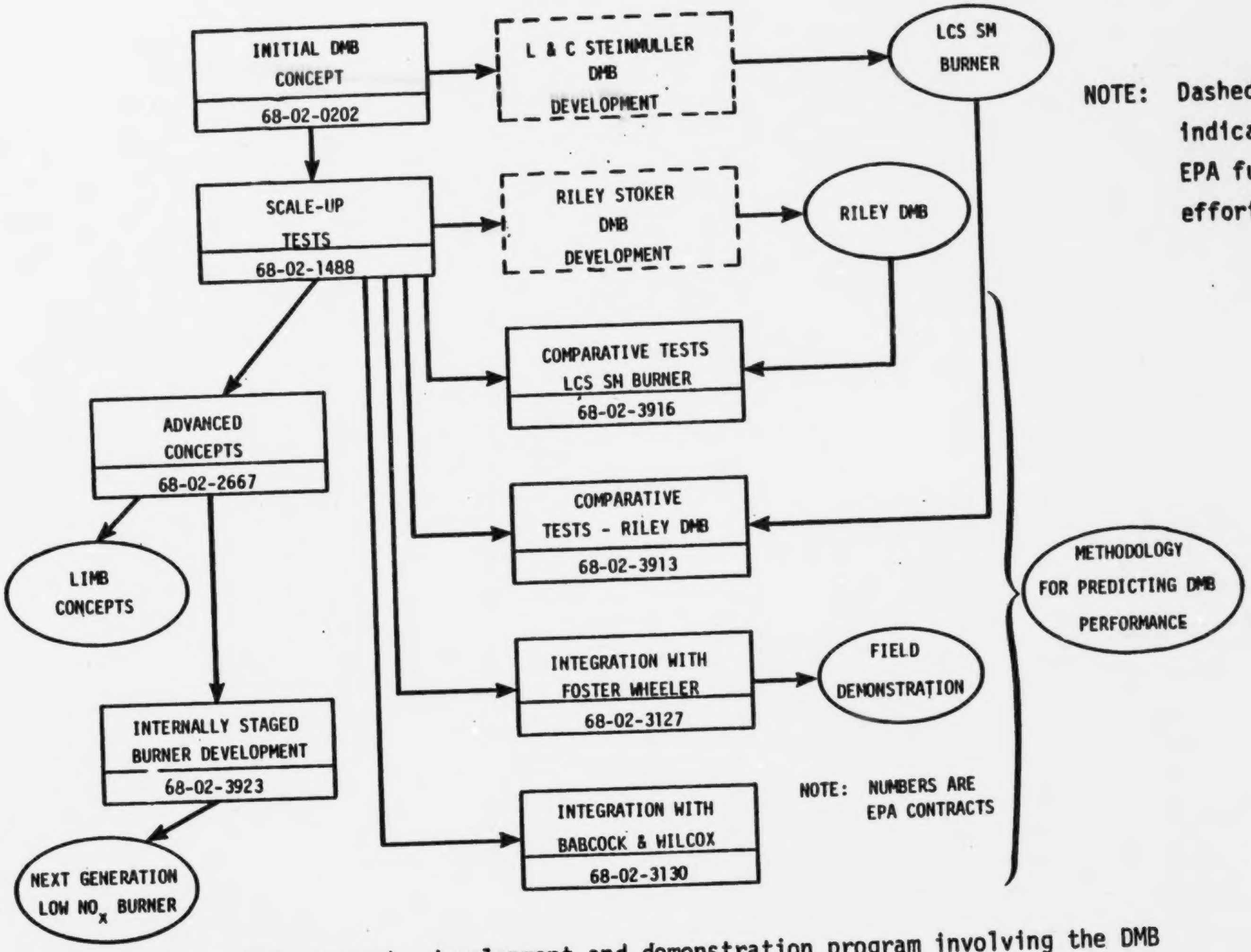
- Two adjustable air registers connected to the secondary air passages to control both the air flowrates and degree of swirl.

- A retractable oil atomizer on the burner axis.

- Ignition and main flame scanner systems for safety. Alternate DMB designs could include central coal nozzles, single secondary air passages or other design changes. The key element is the use of outboard tertiary air ports to achieve staged combustion.

The development history of the DMB is summarized in Figure 1-3. Initial development of the DMB was conducted at the International Flame Research Foundation (IFRF) under EPA Contract 68-02-0202. This included proof-of-concept tests in a research furnace firing at 8.5 x 10^6 Btu/hr. Additional development and scale-up tests were conducted at Energy and Environmental Research Corporation (EER) under EPA Contract 68-02-1488. To provide a standard means of evaluating burner performance, two large-scale test facilities were constructed: the Small Watertube Simulator (SWS) and the Large Watertube Simulator (LWS). The SWS was designed to simulate the thermal environment of a small watertube boiler. It had a capacity of 10 x 10^6 Btu/hr and provided a means of testing burners at moderate scale so that the effects of parameter variations could be evaluated at low cost. The LWS was designed to simulate a large industrial or small utility watertube boiler. The furnace shape was similar to commercial boilers with a hopper bottom, a nose and provision for front-wall firing. The firing capacity of the LWS was 150 x 10^6 Btu/hr which allowed full-scale burners to be evaluated under conditions simulating large commercial systems.

Six DMB configurations were designed and tested. The designs covered a firing rate range of 10-100 x 10^6 Btu/hr as single burners and a four-burner array. The DMBs were research designs with "flexible" parameters so that the effects of burner design variations on NO_x emissions, flame stability and combustion efficiency could be evaluated. Minimum NO_x emissions for each burner were in the range of 0.1 - 0.2 lb/10^6Btu. The results of the tests


INITIAL DMB CONCEPT
68-02-0202
L & C STEINMULLER DMB DEVELOPMENT
LCS SM BURNER
SCALE-UP TESTS
68-02-1488
RILEY STOKER DMB DEVELOPMENT
RILEY DMB
COMPARATIVE TESTS LCS SM BURNER
68-02-3916
ADVANCED CONCEPTS
68-02-2667
COMPARATIVE TESTS - RILEY DMB
68-02-3913
METHODOLOGY FOR PREDICTING DMB PERFORMANCE
LIMB CONCEPTS
INTEGRATION WITH FOSTER WHEELER
68-02-3127
FIELD DEMONSTRATION
INTERNALLY STAGED BURNER DEVELOPMENT
68-02-3923
INTEGRATION WITH BABCOCK & WILCOX
68-02-3130
NOTE: NUMBERS ARE EPA CONTRACTS
NEXT GENERATION LOW NO$_x$ BURNER

NOTE: Dashed boxes indicate non-EPA funded efforts.

Figure 1-3. EPA research, development and demonstration program involving the DMB from LIMB capsule report.

were compiled into a set of design criteria which could be used to apply the DMB concept to commercial burners.

At this point, the development divided into two parallel efforts. One focused on advanced concepts of NO_x and SO_x control. In EPA Contract 68-02-2667 the DMB concept was integrated with sorbent injection for SO_x control. The resulting process was termed "Limestone Injected Multi-stage Burner" (LIMB) and considerable development is continuing in this area. In EPA Contract 68-02-3923 advanced burner concepts are being developed to achieve staging without the need for the outboard tertiary air ports of the DMB.

The other effort focused on the further development and commercialization of the DMB. Two EPA field evaluation programs were established. In EPA Contract 68-02-3127 (the subject of this report) the objective was to evaluate the DMB for boiler applications in the 100-500 x 10^3 lb/hr range which is typical of large industrial and small utility boilers. In Contract 68-02-3130, the objective was to evaluate the application of the DMB technology to larger scale utility boilers. These programs were conducted in conjunction with major US burner/boiler manufacturers: Foster Wheeler (FW) for the industrial demonstration and Babcock & Wilcox (B&W) for the utility demonstration. The industrial field evaluation program has progressed through a field installation and extensive field tests. The parallel utility program is still in progress and will proceed through prototype burner testing in a research furnace only. A scaling methodology will be used to project the DMB performance to full-scale utility boilers.

In parallel with this EPA development, two other burner manufacturers have elected to develop DMBs for commercial offerings. Based on the results of the initial IFRF tests, L&C Steinmuller (LCS), a German burner/boiler manufacturer, developed a commercial DMB, the Staged Mixing (SM) Burner. LCS installed the SM burners in a 700 MW German boiler and demonstrated a 50 percent reduction in NO_x emissions (Leikert and Michelfelder, 1980). The SM burner is now LCS's standard commercial burner offering. Riley Stoker developed a DMB based on the design criteria developed in EPA Contract 68-02-1488 in conjunction with EER. The Riley DMB was tested in research facilities at EER and a field installation is in progress. The results of these independent developments are being integrated with the EPA work in EPA Contracts 68-02-3916 and 68-02-3913 which include tests of the LCS and Riley DMBs, respectively, in the new LWS test facility.

Together these development efforts provide a considerable data base on the performance of DMBs and commercial burners in the LWS and field operating boilers. Table 1-1 demonstrates the extent of this data base which may be used to project DMB performance to a wide range of full scale industrial and utility boilers.

1.2 Program Objectives and Approach

The objective of this program (EPA Contract No. 68-02-3127) was to evaluate the DMB concept on a commercially operated industrial size boiler. The goal was to attain NO_x emission levels less than 0.2 $lb/10^6$ Btu or as low as possible without adverse effects on boiler operability and durability, thermal efficiency and the emissions of other pollutants. The field evaluation involved: 1) translation of the development burner test data into practical prototype DMBs; 2) verification of the prototype burner performance through testing in a research furnace; 3) construction of field operable DMBs, installation of these burners in the field boiler and evaluation of performance under typical operating conditions; 4) documentation of the results; and 5) input to the parallel utility field evaluation (EPA Contract No. 68-02-3130).

To accomplish the program objectives, the efforts were organized into the following nine tasks:

1. Program Definition
2. Prototype Construction and Testing
3. Boiler Characterization
4. Burner Installation

TABLE 1-1. DMB DATA BASE

BURNER OR COMPONENT MANUFACTURER	BURNER	RESEARCH FACILITY (LWS) TEST	FIELD EVALUATION
FOSTER WHEELER	INTERVANE (PRE-NSPS)	X	FIELD DEMONSTRATION: BURNER REPLACEMENT AT A SMALL UTILITY BOILER
	DMB	X	
BABCOCK AND WILCOX	CIRCULAR (PRE-NSPS)	X	FIELD TEST
	DUAL REGISTER (NSPS)	X	FIELD TEST
	DMB	X	
RILEY STOKER	FLARE (PRE-NSPS)	X	FIELD TEST
	CCV (PRE-NSPS)	X	FIELD TEST
	DMB	X	
L&C STEINMULLER	SM	X	FIELD TEST

5. Performance Evaluation
6. Industry Coordination
7. Boiler Restoration
8. Data Analysis
9. Design Approach Documentation

Figure 1-4 shows the interaction of these tasks to achieve the program objectives. In Task 1, all of the basic elements of the program were planned including boiler selection, burner design and establishment of a measurements plan. A host site boiler was selected and negotiations with the operator completed so that a firm schedule for the remaining aspects of the study could be established. The final burner design was established following host boiler selection. Based on the final burner design established in Task 1, a prototype burner including all controls was constructed, installed in the Large Watertube Simulator Furnace (LWS) and evaluated using several coals as part of Task 2. In addition, the commercial burner used in the host site boiler was evaluated in the LWS to provide a direct comparison with the prototype DMB and to identify any potential problems. At the conclusion of Task 2, the DMB design was ready for fabrication and installation in the host boiler.

While Task 2 was being accomplished, the Task 3 - Boiler Baseline Evaluation of the host unit was initiated. This effort established the normal operating characteristics as well as the potential for reducing NO_x emissions by utilizing various combustion modification techniques associated with operating point changes. Following the baseline characterization, the low NO_x coal burners and all support systems were installed in the host boiler in task 4. Checkout tests were conducted to ensure that the DMBs could perform in a manner similar to the original burners.

At the completion of Task 4, the low emission burner system was ready for extensive evaluation. The retrofitted boiler was operated over a sufficient range of conditions consistent with the steam requirements to define the multi-burner optimization of emissions. Once this was defined then long term evaluations were conducted with the boiler operating under a

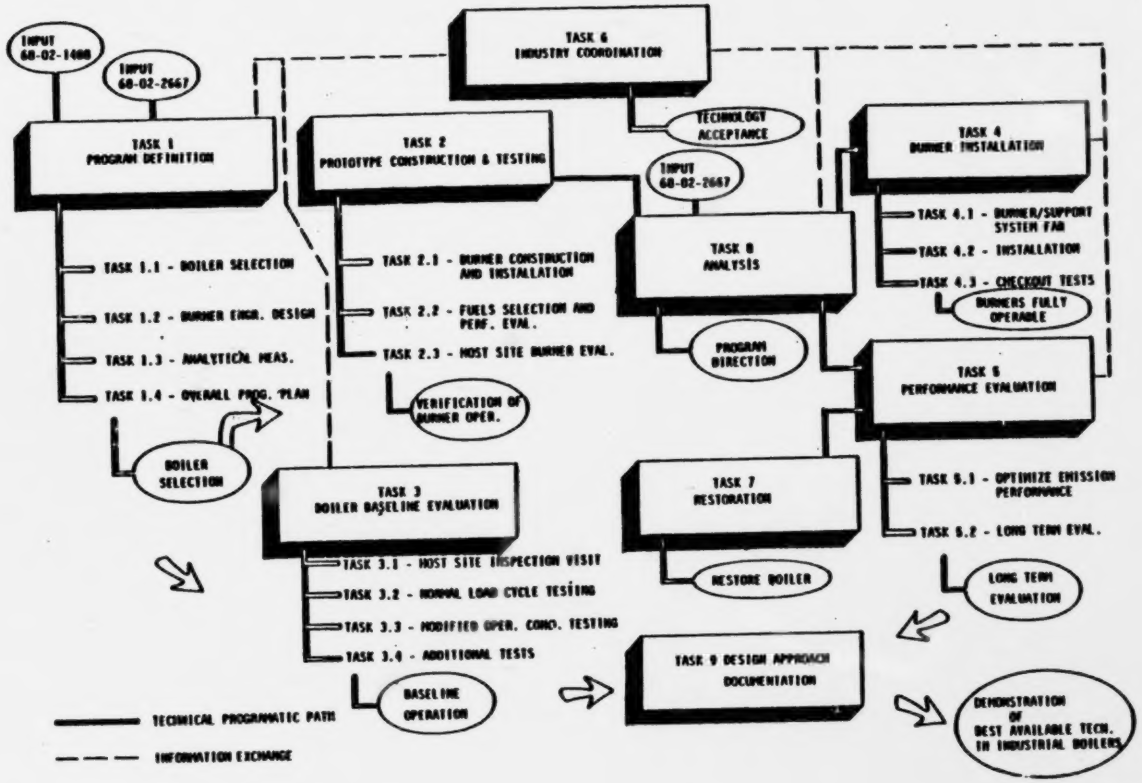

INPUT 68-02-1400
INPUT 68-02-2667
TASK 1 PROGRAM DEFINITION
TASK 1.1 - BOILER SELECTION
TASK 1.2 - BURNER ENGR. DESIGN
TASK 1.3 - ANALYTICAL MEAS.
TASK 1.4 - OVERALL PROG. PLAN
BOILER SELECTION
TASK 6 INDUSTRY COORDINATION
TECHNOLOGY ACCEPTANCE
TASK 2 PROTOTYPE CONSTRUCTION & TESTING
TASK 2.1 - BURNER CONSTRUCTION AND INSTALLATION
TASK 2.2 - FUELS SELECTION AND PERF. EVAL.
TASK 2.3 - HOST SITE BURNER EVAL.
VERIFICATION OF BURNER OPER.
INPUT 68-02-2667
TASK 8 ANALYSIS
PROGRAM DIRECTION
TASK 4 BURNER INSTALLATION
TASK 4.1 - BURNER/SUPPORT SYSTEM FAB
TASK 4.2 - INSTALLATION
TASK 4.3 - CHECKOUT TESTS
BURNERS FULLY OPERABLE
TASK 5 PERFORMANCE EVALUATION
TASK 5.1 - OPTIMIZE EMISSION PERFORMANCE
TASK 5.2 - LONG TERM EVAL.
LONG TERM EVALUATION
TASK 3 BOILER BASELINE EVALUATION
TASK 3.1 - HOST SITE INSPECTION VISIT
TASK 3.2 - NORMAL LOAD CYCLE TESTING
TASK 3.3 - MODIFIED OPER. COND. TESTING
TASK 3.4 - ADDITIONAL TESTS
BASELINE OPERATION
TASK 7 RESTORATION
RESTORE BOILER
TASK 9 DESIGN APPROACH DOCUMENTATION
DEMONSTRATION OF BEST AVAILABLE TECH. IN INDUSTRIAL BOILERS
TECHNICAL PROGRAMMATIC PATH
INFORMATION EXCHANGE

Figure 1-4. Program organization.

"normal duty cycle". At the conclusion of this task, the boiler/burner system was inspected and the condition of all systems documented. Task 7 involved the restoration of the boiler.

The remaining Tasks 6 and 8 were accomplished concurrent with all of the other tasks. Lastly, the Final Report, Task 9, involved integration of the overall effort into an evaluation of this technology's applicability to coal-fired industrial boilers. This included an experimental evaluation of mixing patterns produced by multiple burner arrays and an economic evaluation of the DMB applied to a new boiler.

This program was conducted with EER as the prime contractor and Foster Wheeler Development Corporation (FW) as a major subcontractor. Foster Wheeler Development Corporation subcontracted the technical effort to its sister company, Foster Wheeler Energy Corporation. Foster Wheeler's involvement in the prototype burner portion of the program included burner design based on the DMB design criteria, Foster Wheeler burner components and Foster Wheeler proprietary burner design parameters, as well as burner construction. EER developed the DMB design criteria, installed the prototype burners in the LWS test facility and conducted the burner tests. In the field evaluation, Foster Wheeler was primarily responsible for boiler selection, coordination with the host, retrofit design, equipment installation, unstaged checkout testing and assessment of corrosion. EER and Foster Wheeler worked together on most other aspects of the program.

1.3 Program Chronology

It was originally intended to conduct field installations/evaluations on two boilers. However, due to the complexity and cost of the installation on the initial boiler, the second field installation was cancelled.

The overall program schedule is illustrated in Figure 1-5. Work began in October, 1978. The initial task was to select host boilers and negotiate host agreements. The boiler selection process was coordinated by FW. FW reviewed the characteristics of all FW US boilers and a number of candidate

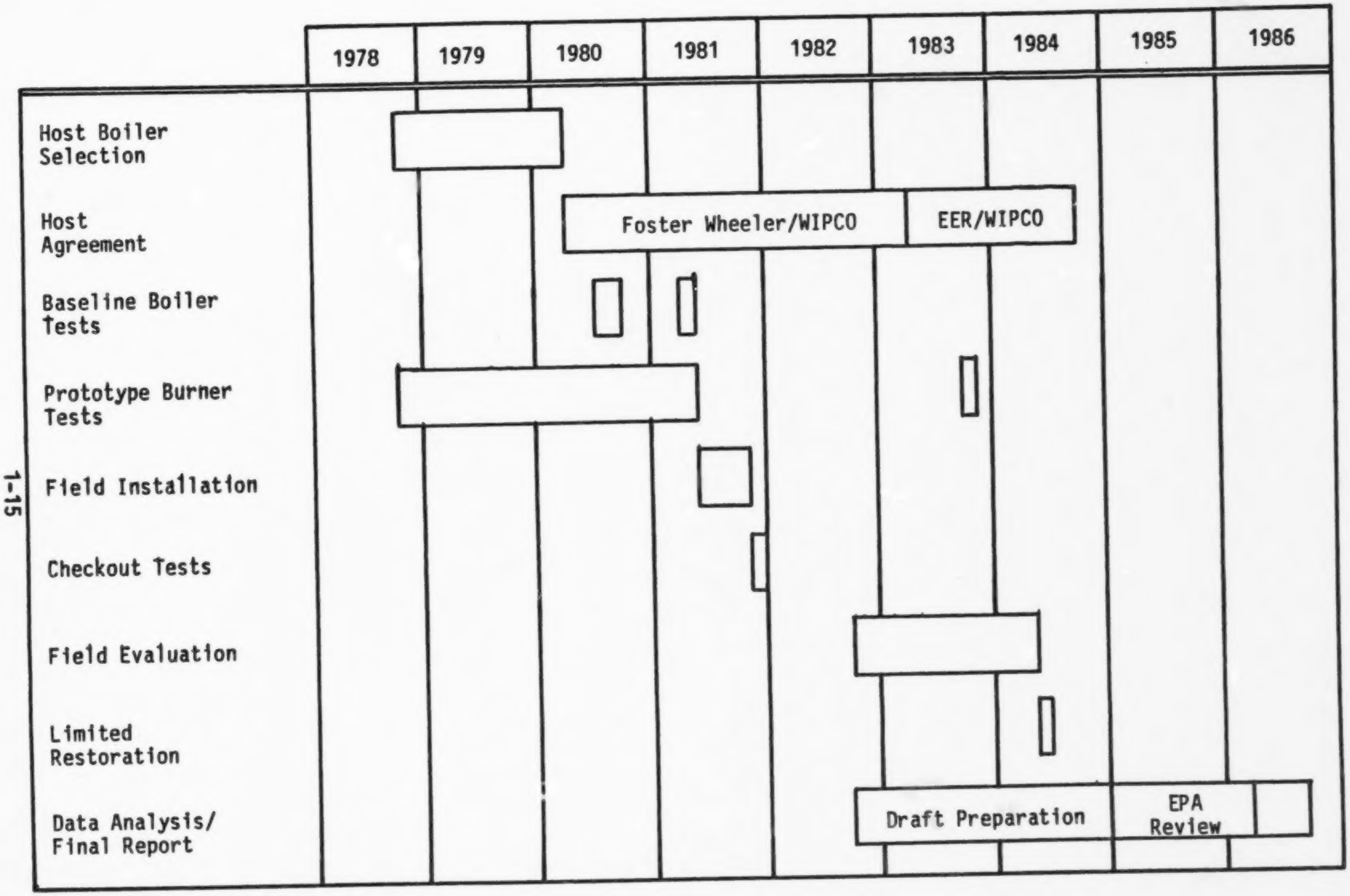


Figure 1-5. Program schedule.

units were selected. Since all were equipped with FW Intervane burners with capacity of about 80 x 10^6 Btu/hr, the initial prototype burner was designed based on generic specifications rather than the final specifications of the host boiler. Also, FW supplied an 80 x 10^6 Btu/hr Intervane burner for testing in the LWS in the summer of 1979. After considerable negotiation, a host agreement was obtained from Western Illinois Power Cooperative (WIPCO) for the use of Pearl Station Unit 1 in February, 1980. This is a small (20 MW) front-wall fired utility boiler with characteristics similar to industrial boilers of comparable size (215 x 10^3 lb/hr). The agreement provided for burner installation and testing as well as restoration at the completion of the program.

In March 1980, Foster Wheeler installed corrosion panels in the furnace during a scheduled outage. EER and FW conducted a field test in the summer of 1980 to provide a baseline for comparison with subsequent DMB performance. NO_x emissions were approximately 1.0 lb/10^6 Btu. Additional tests were conducted in March, 1981 immediately prior to the low NO_x burner retrofit. During this period, FW monitored corrosion rates by means of ultrasonic tube thickness measurements at scheduled outages.

The prototype DMB design was completed in the Fall of 1979. The prototype burner was tested in the LWS test facility in December, 1979. These tests indicated that the operability, flame shape, smoke and CO emissions of the prototype DMB were comparable to the Intervane burner. The NO_x emissions were much lower (as expected) with minimums of about 0.2 lb/10^6 Btu; however, burner flame stability was marginal. Unfortunately, the LWS test facility had exceeded its design life and furnace wall deterioration required that the tests be terminated prior to the completion of the test series. It was estimated that about two months of additional testing would be required to obtain data sufficient for a field installation. Allowing for the time required to: rebuild the LWS, retest the prototype DMB, design and fabricate the field operable burners and install the burners during a scheduled outage, a significant delay in the program was anticipated. To minimize this delay, a decision was made to modify the DMB to incorporate FW proprietary burner exit geometry. Burners with this exit geometry were known to have adequate flame stability operating with overfire air port staging. The plan was to proceed with the design of the field operable burners during the rebuilding of the LWS. The prototype burner with FW exit geometry would then be tested in the LWS to confirm its performance immediately prior to the scheduled field installation. Since flame stability was not a question, the field installation could proceed and the unit operation could resume with the tertiary air ports closed, if problems with the tertiary air ports were identified. A confidentially agreement was negotiated with FW to protect the FW proprietary design parameters. The key provisions were non-disclosure of the specific exit geometry, performance optimizing parameters and data for operation outside the DMB operating range (burner zone stoichiometry greater than 85 percent T.A.).

The rebuilding of the LWS was completed in the fall of 1980. The new LWS incorporated some design changes to make it more representative of field units. This included a geometry nearly identical to Pearl Station Unit 1, refractory insulation to match the thermal characteristics of full scale industrial/utility boilers and a modified exhaust duct

The initial prototype burner design was retested to provide a direct comparison of performance in the old and new LWSs. These tests confirmed the earlier results but showed that the operation was limited to a burner zone stoichiometry in excess of 85 percent T.A., substantially higher than the design point, 70 percent T.A. Lower burner zone stoichiometries resulted in flame instability. Next, the prototype burner was modified to incorporate the FW exit geometry and retested in the LWS. Satisfactory performance at the burner design point (70 percent T.A.) was verified and the installation at Pearl Station proceeded in the Spring of 1981. Subsequently, the burner design with the FW parameters was tested in another large test facility at EER, the medium tunnel (MT), to provide an evaluation of the effects of furnace confinement. Also, a final series of tests was conducted in the LWS with the initial prototype burner design to determine the modifications necessary to achieve adequate flame stability and optimum NO_x emissions performance.

The DMB installation at WIPCO required considerably more time than anticipated due to a series of problems unrelated to the DMB concept. The major problem was in interfacing a new burner management system to the existing boiler wiring. These problems were solved and the unit was returned to service in August, 1981. Foster Wheeler conducted a series of tests to ensure that the burners could operate over the full normal load range without operational problems with the tertiary air ports closed. At this point, the field evaluation was suspended pending availability of additional EPA funding. The operation of the unit was turned over to the boiler operators. They operated the unit over the normal duty cycle for 14 months. During this period, the WIPCO management was pleased with the burner operation and elected to reduce the scope of the restoration to at maximum, disabling of the tertiary air port operation and removal of the corrosion panels.

Following availability of additional EPA funding, optimization tests with the tertiary air ports open commenced in November, 1982 and continued for 17 months. A comprehensive series of tests was conducted over a range of burner settings. Minimum NO_x emissions of 0.3 $lb/10^6$ Btu were measured under controlled conditions. With the unit operating under the direction of the operators, the NO_x emissions were in the range of 0.5 $lb/10^6$ Btu. Based on burner performance during this period, WIPCO elected to eliminate the requirement for disabling the tertiary air ports at the end of the test program.

The restoration occurred in April, 1984 and was limited to corrosion panel removal and some minor adjustments/repairs to the burners and burner management system. At present, the unit is operating with the tertiary air ports closed. However, the tertiary air ports are fully operational and could be opened at anytime.

Annual reports were submitted for the first three years of the program effort and have been published by EPA. The first annual report details the boiler selection process and the initial prototype burner design. The second annual report discusses the initial prototype burner tests, the measurement procedures used throughout the program and initial data from the boiler baseline evaluation. The third annual report details the tests for the prototype burner with the FW parameters, presents additional data on the boiler baseline performance and discusses the plans for the field installation.

During the program, a number of technical papers were presented at technical conferences. Also, coordination with industry was achieved via a technical panel meeting where representatives of equipment manufacturers and boiler operators were present and via participation of the program manager in the Air Pollution Control Association (APCA) Industrial Combustion Technical Committee (TS 2.2).

1.4 Guide To The Report

This report is organized into three volumes. This volume (I) presents detailed technical results. Volume II contains Appendices of information discussed in Volume I. Volume III is a guideline manual which summarizes the results in a format that can be used to guide future DMB installations.

The remainder of Volume I is organized as follows:

2.0 Host Boiler

The boiler selection process is summarized. The characteristics of the host boiler are summarized. The results of the tests of the baseline boiler test are presented.

3.0 Prototype DMBs

Testing of DMBs in test facilities are presented. This includes tests of the FW intervane burner in the old LWS, the initial prototype DMB in the old and new LWS, the DMB incorporating FW parameters in the new LWS and MT and the final modified prototype burner in the new LWS.

4.0 DMB Field Evaluation

The design and installation of the DMBs at the host site are discussed. The results of the field evaluation are presented including short term optimization tests, long term operational tests and corrosion measurements.

5.0 Comparison of Prototype and Field Operating DMBs

The data from DMB tests in the research furnace and field tests are compared. Methods of projecting the results of this program to other field operating units are presented.

6.0 Application of the DMB Concept

The factors influencing the use of the DMB in other applications are presented. The cost impacts of applying the DMB to new utility boilers are estimated.

7.0 Conclusions and Recommendations

8.0 References

2.0 HOST BOILER

The host boiler for the DMB demonstration was Pearl Station Unit 1 owned and operated by Western Illinois Power Cooperative (WIPCO). The WIPCO boiler was selected based on a comprehensive review of the U.S. boiler inventory and discussions with several potential hosts. The boiler selection process was discussed in detail in the First Annual Report and is summarized in the following subsection. The WIPCO unit is a small utility boiler representative of a large class of small utility and large industrial boilers. The design of the WIPCO unit is detailed in subsection 2.2. A field test of the WIPCO unit was conducted prior to the DMB retrofit to establish emissions and efficiency baselines. The results of these tests were discussed in detail in the Second and Third Annual Reports and are presented in subsection 2.3.

2.1 Boiler Selection

Initially, two field evaluations of the DMB were planned in this program. The boiler selection process focused on identifying two host boilers which were representative of a large fraction of the existing and projected industrial boiler inventory. Also, it was the intent to select boilers of distinctly different characteristics from an NO_x control point-of-view to span a wide range of boiler characteristics and thus broaden the potential application of the test results. The characteristics of the existing and projected industrial boiler population were assessed focusing on the ranges of burner and furnace designs and duty cycles. Boiler inventory data were obtained from several DOE and EPA sponsor studies and the America Boiler Manufacturers Association (ABMA). Design and operating data were obtained from several industrial boiler and burner manufacturers along with drawings and specifications of specific boilers. Based on these data, a general specification for representative industrial boilers was established. The inventory data were detailed in the First Annual Report. The general specification is summarized in subsection 2.1.1.

The DMB was developed principally for new installations. However, this field evaluation program required a retrofit installation. The DMB has several characteristics which have the potential to cause installation and operational problems on a retrofit basis. These DMB requirements are discussed in subsection 2.1.2.

Based on the industrial boiler inventory, the specific requirements of the DMB, and the objectives of the field evaluation program, selection criteria for the host boiler sites were formulated and a pair of boiler descriptions representing the ideal host boiler sites were defined. Then, these criteria were applied to the boiler inventory and several potential host boilers were identified and ranked according to their overall desirability to the program. The owners/operators of the higher ranked boilers were contacted by Foster Wheeler Sales and Service personnel. Where the responses were favorable, meetings were held between the owners/operators of the boilers, Foster Wheeler and EER personnel with the objective of providing more information on the program and determining the conditions required for participation. These discussions led to selection of the WIPCO unit as the initial demonstration site. The selection process is summarized in subsection 2.1.3.

2.1.1 Industrial Boilers

The boiler size range of interest to this program is 100-1000 x 10^3 lb/hr steam raising capacity firing pulverized coal. Boilers in this range are used for both industrial steam raising and small utility power generation.

The capacity range of industrial boilers is usually considered to be larger than commercial boilers but smaller than utility boilers. However, this classification is by no means clear cut. The ABMA defines an industrial boiler as "any boiler over 10,000 lb/hr of steam not used by a utility company" (Axtman, 1978). Babcock & Wilcox has a separate sales organization for industrial boilers covering boilers up to 1,000,000 lb/hr steam and 1800 psig steam pressure (Godshalk, 1978). This apparent confusion between industrial and utility boiler definitions stem from the fact that the terms industrial and utility normally denote the use of the steam and therefore applies to any capacity.

The end use of the steam provides one distinct difference in boiler design specifications. Modern utility boilers generally produce steam at high temperature (1000°F), and high pressure (up to 3500 psig) and reheat steam to high temperature at some intermediate pressure. These conditions allow the operation of high efficiency steam turbine cycles. However, steam from industrial boilers is used for a wide range of industrial processes in which high pressure, high temperature steam is not required. This difference in steam conditions results in differences in the size and arrangement of industrial and utility boiler convective passes. Figure 2-1 shows the percentage of heat absorbed by steam in the furnace and convective pass in industrial boilers as functions of steam conditions. For all conditions, the furnace absorbs about half of the heat to boil water. At low pressure, low temperature saturated steam conditions, all of the convective heat transfer is used to boil water. As steam temperature and pressure are increased, some heat is required to superheat steam and the amount of heat required to warm the feed water becomes great enough to justify a separate economizer pass. This results in a smaller convective boiler pass. These trends continue as steam pressure and temperature are increased and at a steam pressure of 1900 psig and steam temperature of 1000°F, the boiling convective pass is eliminated and all boiling occurs in the furnace tube walls.

The burner/boiler variables which primarily influence NO_x are independent of the steam conditions or end use (industrial or utility). Table 2-1 shows the relationships between some of these variables and boiler capacity. Industrial pulverized coal-fired steam generators range in size from 120,000 lb/hr to approximately 900,000 lb/hr of steam. The smaller units, up to about 300,000 lb/hr capacity, typically have four burners and two pulverizers. Larger units utilize as many as 12 burners and 4 pulverizers. Utility steam generators range in capacity from 200,000 lb/hr to over 5,000,000 lb/hr. Thus, there is an overlap region where industrial and utility steam generator designs are quite similar. Other parameters, shown in Table 2-1 also support this contention in that all units are

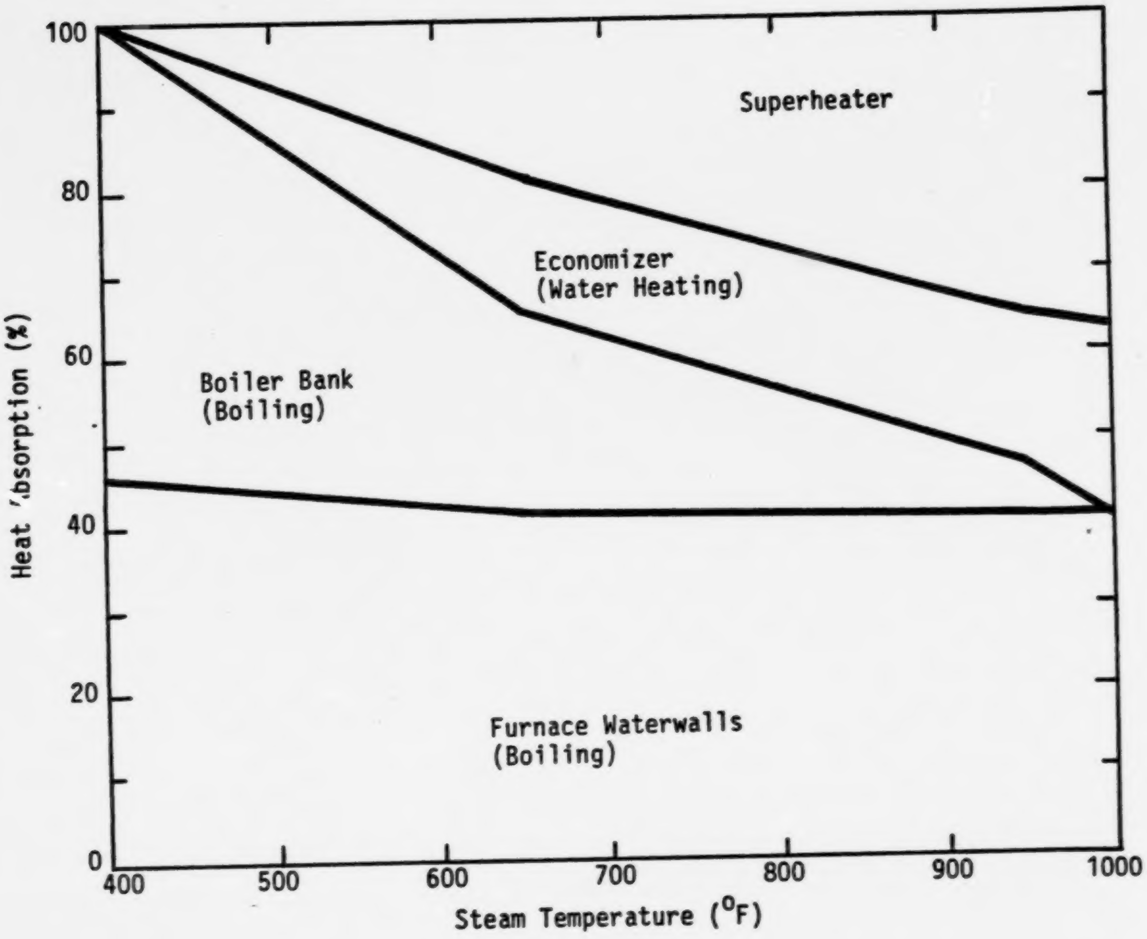
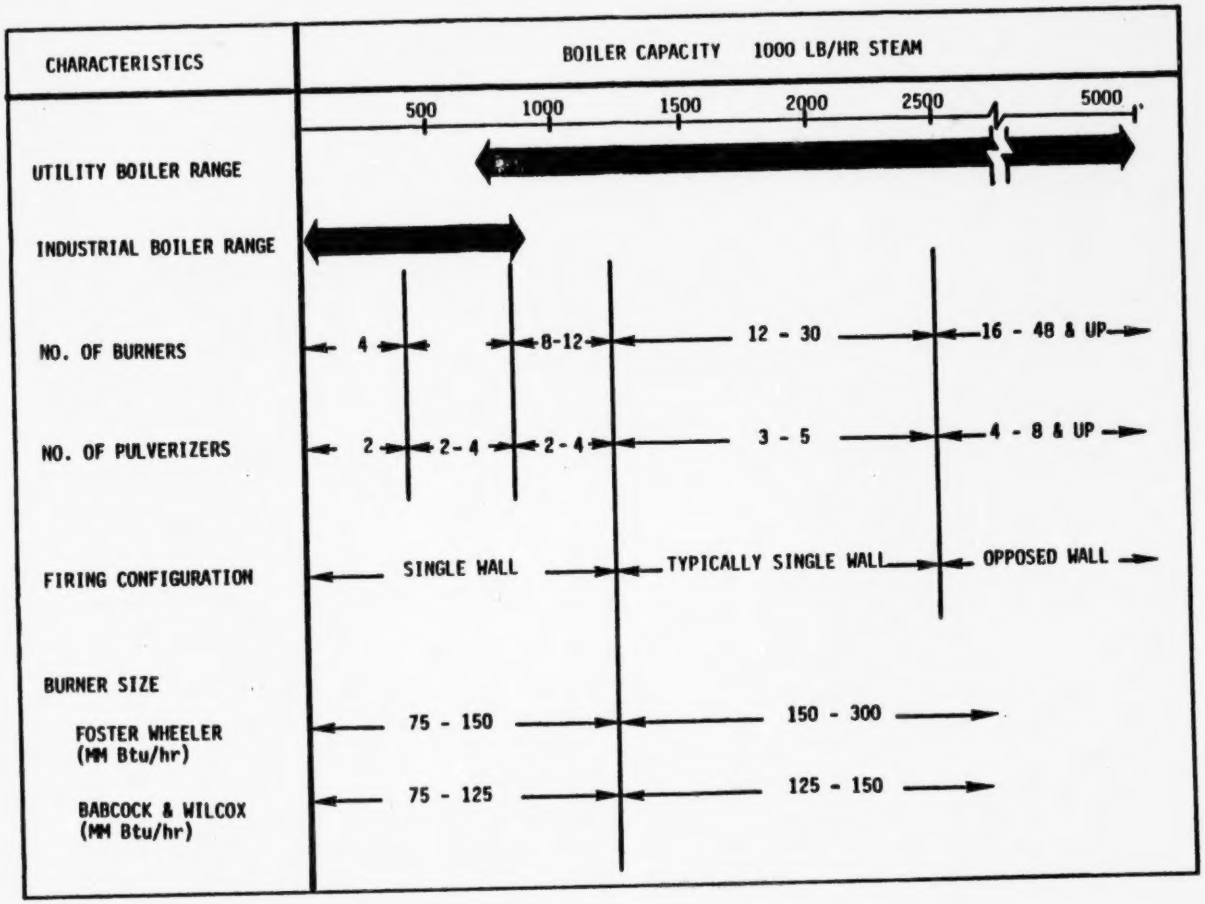


Figure 2-1. Effect of steam conditions on heat absorption within a unit.

TABLE 2-1. BOILER DESIGN COMPARISON



typically single-wall fired and within the industrial range, major manufacturers of boilers utilize approximately the same capacity burners. It would appear from this information that a large industrial boiler would be representative of a small utility boiler. Further, Table 2-1 also shows that many of the larger single-wall fired utility boilers utilize burners with capacities of 125-300 x 10^6 Btu/hr. Thus, if the larger host unit utilized burners in this capacity range, the applicability of the results could be extended to cover larger capacity boilers.

Table 2-2 compares the design and operating characteristics of five Foster Wheeler industrial and utility boilers in two size ranges: 4-burner 250,000 lb/hr units and 6-burner 400,000 lb/hr units. Figures 2-2 and 2-3 show side views of the 4-burner and 6-burner units respectively. The unit numbers refer to the boiler selection process discussed in subsection 2.1.3. Functionally, these units are nearly identical. All use medium speed mills and are equipped with Foster Wheeler Pre-NSPS Intervane Burners. The most obvious difference between the industrial and utility units is the larger superheat surface of the utility units. This results from the higher utility boiler superheat temperatures. Most utility units require steam temperatures above 900°F, whereas few industrial units require steam temperatures above 700°F. In both types of units, steam generator efficiencies are maintained at high levels by adjusting feed water temperature, economizer surface and air preheater surface so that flue gas temperatures are all within a narrow range.

The lower drum pressures of the industrial units result in lower saturation temperatures. Since boiling occurs in the furnace water wall, the two phase mixture is approximately at the saturation temperature. For the units shown, the maximum saturation temperature difference is 65°F (475°F vs. 540°F). The outside tube surface temperatures are about 100°F higher (575°F vs. 650°F). The effect of this temperature difference on NO_x formation should be negligible. The slightly lower tube metal temperature associated with the lower drum pressure of the industrial boiler is, therefore, of no concern from an NO_x control viewpoint.

TABLE 2-2. DESIGN PARAMETER COMPARISON

BURNERS	4			6	
INVENTORY NO. APPLICATION	Unit 1 Utility	Unit 4 Utility	Unit 2 Industrial	Unit 16 Utility	Unit 9 Industrial
MCR (10^3 lb/hr)	245	245	266	385	400
S.H. Temp (°F)	905	905	650	905	705
S.H. Press. (psig)	880	880	728	875	525
Feedwater Temp. (°F)	355	370	360	440	230
Sec. Air (°F)	510	618	583	581	543
Temp. Gas Lvg. Boiler (°F)	724	700	760	750	725
Temp. Gas Lvg. AH (°F)	327	325	360	319	312
Unit Eff. (%)	86.39	85.27	87.38	87.47	88.62
Design Fuel (btu/lb)	11,300	9,000	13,000	12,700	14,100
Ash (%)	9.5	8.0	11.51	7.86	5.00
H_2O (%)	11.0	20.0	4.26	5.96	4.00
Drum Press.	968	965	670	970	450
Sat. Temp. (°F)[*]	540	540	500	540	475
BZLR[+] (10^3 Btu/hr-ft^2)	155.8	186.7	179.7	198.1	229.9

[+] Burner Zone Liberation Rate

[*] Tube metal surface temperature approximately 100°F higher

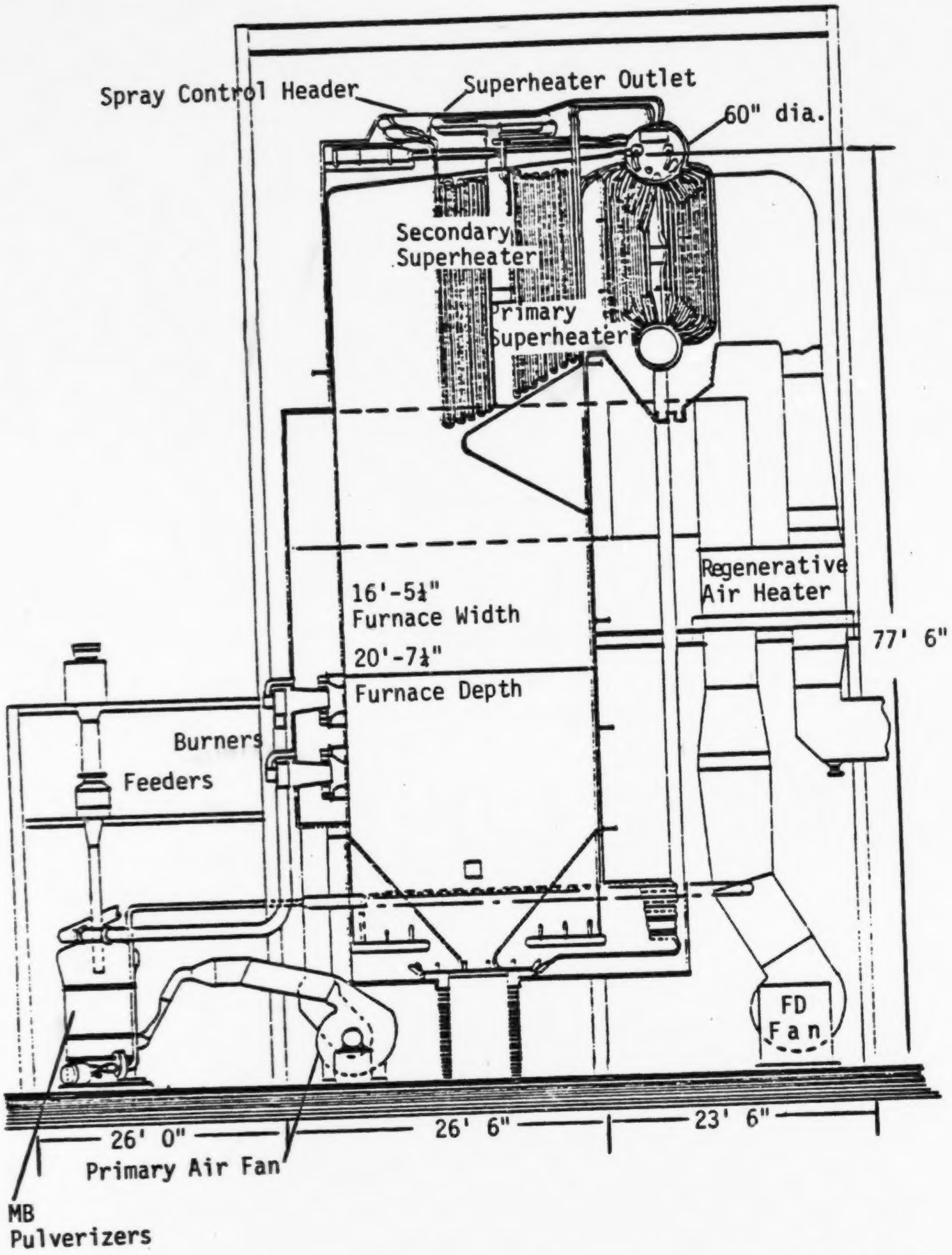

Spray Control Header
Superheater Outlet
60" dia.
Secondary Superheater
Primary Superheater
Regenerative Air Heater
16'-5½" Furnace Width
20'-7½" Furnace Depth
77' 6"
Burners
Feeders
FD Fan
26' 0"
26' 6"
23' 6"
Primary Air Fan
MB Pulverizers

Figure 2-2. Side view of Unit No. 1, a 245,000 lb/hr utility boiler.

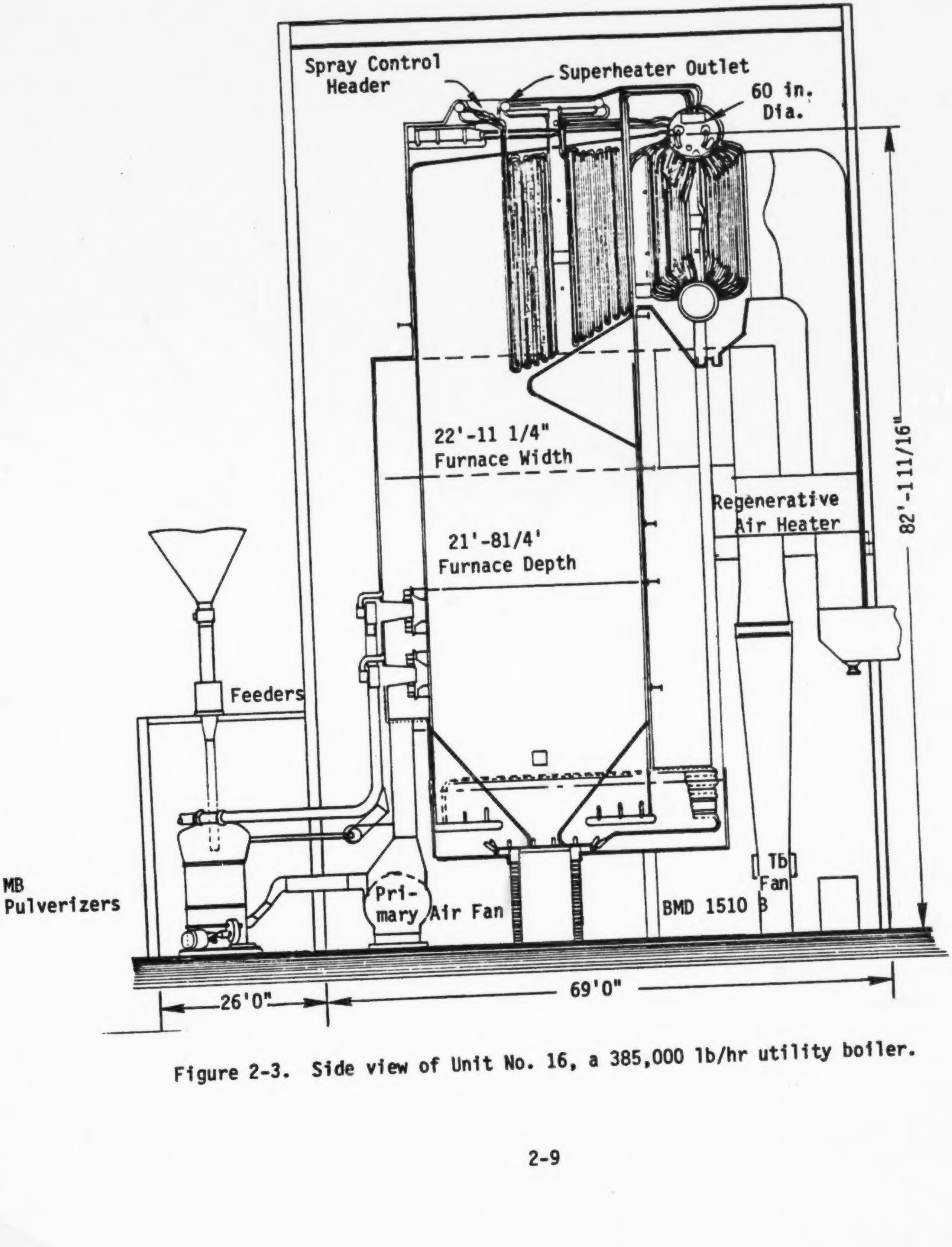
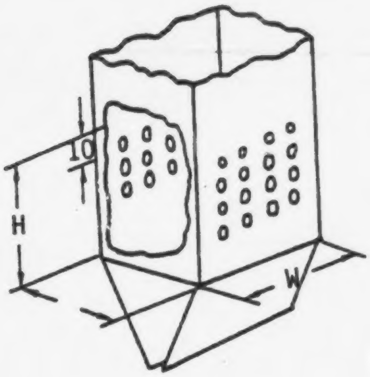

Spray Control Header
Superheater Outlet
60 in. Dia.
22'-11 1/4" Furnace Width
21'-81/4' Furnace Depth
Regenerative Air Heater
82'-111/16"
Feeders
MB Pulverizers
Primary Air Fan
Tb Fan
BMD 1510 B
26'0"
69'0"

Figure 2-3. Side view of Unit No. 16, a 385,000 lb/hr utility boiler.

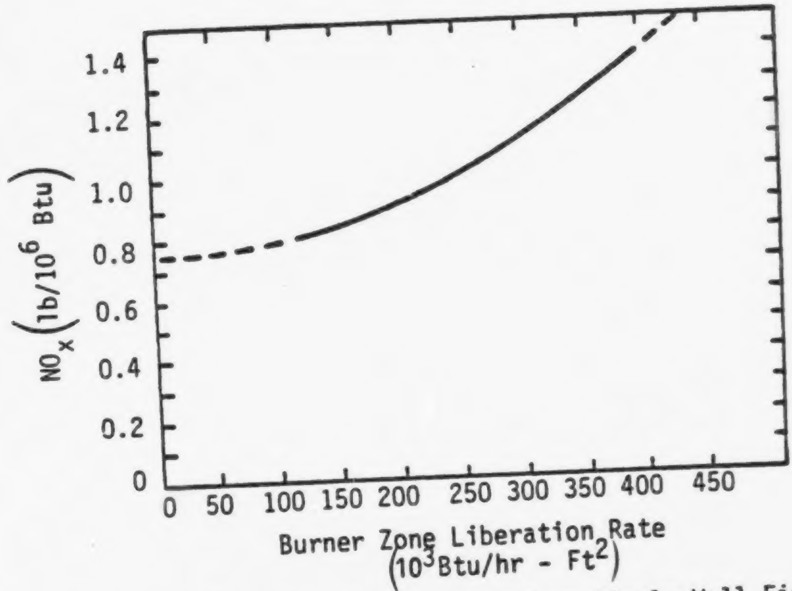
The Burner Zone Liberation Rate (BZLR) is Foster Wheeler's index of the heat release per unit cooled surface area in the lower furnace (Vatsky, 1979). Foster Wheeler has found that the BZLR can be related to NO_x emissions from their coal-fired Pre-NSPS Intervane Burner. Figure 2-4a shows the definition of the cooled surface area used by Foster Wheeler: the area of the 6-sided box starting at the hopper knuckle and extending 10 feet above the top row of burners and including all cooled surface area within that volume. Figure 2-4b shows the general trend of NO_x field test data for Pre-NSPS Intervane Burners in single wall fired furnaces as a function of BZLR. For the five boilers listed in Table 2-2, there is no relationship between BZLR and boiler type (utility or industrial). In each case, the BZLR represents a balance between the requirements of each unit's coal characteristics, firing system and circulation system as determined by the boiler purchaser's specifications.

The boiler duty cycle is of interest also. Pulverized coal fired steam generators are designed to operate at part load with one pulverizer in service and up to full load with all pulverizers in service. In some cases where four pulverizers are used, the unit must also attain full load, meeting all guarantees, with one pulverizer out of service. Also, the unit must be capable of ramping up to full load, and down, as pulverizers (and their associated burners) are taken in and out of service as needed. This requires that the turndown of most burners be 2.5/1 (i.e., stable operation can be maintained down to 40 percent of the burner's maximum capacity). Further, the firing system must operate over this range without requiring constant adjustment. Normally, the only in-service adjustments to the burners occur when the air control dampers (registers) are changed from the "open" to the "closed" position when the burners are removed from service. However, in some units, the operators may adjust the registers periodically (up to several times per shift) to optimize flame characteristics. However, commercial burners must perform reliably and safely without continuous adjustments. Since similar firing equipment is used on both industrial and utility boilers, the operating requirements are similar also. Generally, either type of unit will operate at some specified steady load until required to ramp up or down to some new operating point. The controls and firing



A. Surface Used for Correlation

(Vatsky, 1979)



B. Uncontrolled NO_x Emissions from Single-Wall Fired Units

Figure 2-4. Foster Wheeler NO_x emission correlation.

methods used to achieve this operation are essentially the same for industrial and utility equipment. The most significant transient conditions occur during start up or shut down when the danger of explosion from unbalanced fuel and air supplies is greatest. There is no difference in the safety requirements for either type of boiler. Although the load requirements of any specific utility steam generator may differ significantly from a specific industrial unit, the load following capabilities of the boiler will be virtually indistinguishable. Also, the load cycle requirements of a unit of one type maybe identical to some unit of another type.

In summary, although boiler geometries, burner configurations, and firing systems may vary depending on individual specifications, these variations have only minor effects on NO_x forming parameters. Burner design, BZLR, specific furnace design and coal quality are the primary parameters affecting NO_x emissions. Among the population of steam generators investigated as part of the boiler selection process, no effects on NO_x from other parameters were discerned. The major difference between industrial and utility boilers in the 100-1000 x 10^3 lb/hr capacity range is the steam conditions. While this results in some design differences, they are largely restricted to the convective pass and affect the size and shape of the furnace only slightly with little if any affect on NO_x emissions. Firing system and emission test data obtained from units of either type will be applicable to and representative of the other type when variability and equipment specifications are taken into account.

Based on the information presented in this section and the evaluation of industrial boiler inventory presented in the First Annual Report, the following general specifications of industrial boilers were prepared:

1. Firing Configuration - Configurations other than single-wall firing are insignificant statistically for industrial size boilers.

2. Steam End Use - Differences in design between industrial and utility are primarily in the convective pass design. Differences in parameters which influence NO_x emissions are negligible.

3. Boiler Capacity - Industrial and utility boilers in the capacity range of 100-1000 x 10^3 lb/hr steam have similar designs. The general trend is towards larger units.

4. Burner Size and Number - The smaller units generally have four burners of about 75 x 10^6 Btu/hr capacity. The larger units generally have 8-12 burners of about 125 x 10^6 Btu/hr capacity.

5. Burner Spacing - Burners are generally spaced to evenly distribute the flames within the furnace. Burner spacing increases with increasing capacity and is reported to have a significant influence on NO_x emissions.

6. Manufacturer - The Pre-NSPS designs of the four manufacturers for industrial size units are similar.

7. Fuel - Eastern and Central bituminous coals are predominate in the current industrial boiler inventory. However, future boiler generation are projected to utilize more western sub-bituminous coals.

8. Combustion Intensity - A large percentage of existing units are in eastern and central coals are in the 17-21 x 10^3 Btu/hr-ft^3 range. However, there is a trend toward lower combustion intensity in new units, especially those designed for western coals.

Figure 2-5 shows the distribution of industrial and utility boilers in the United States, including the number of units (population) and capacity. The 100-1000 x 10^3 lb/hr capacity range includes the following fractions of the boiler population and total capacity:

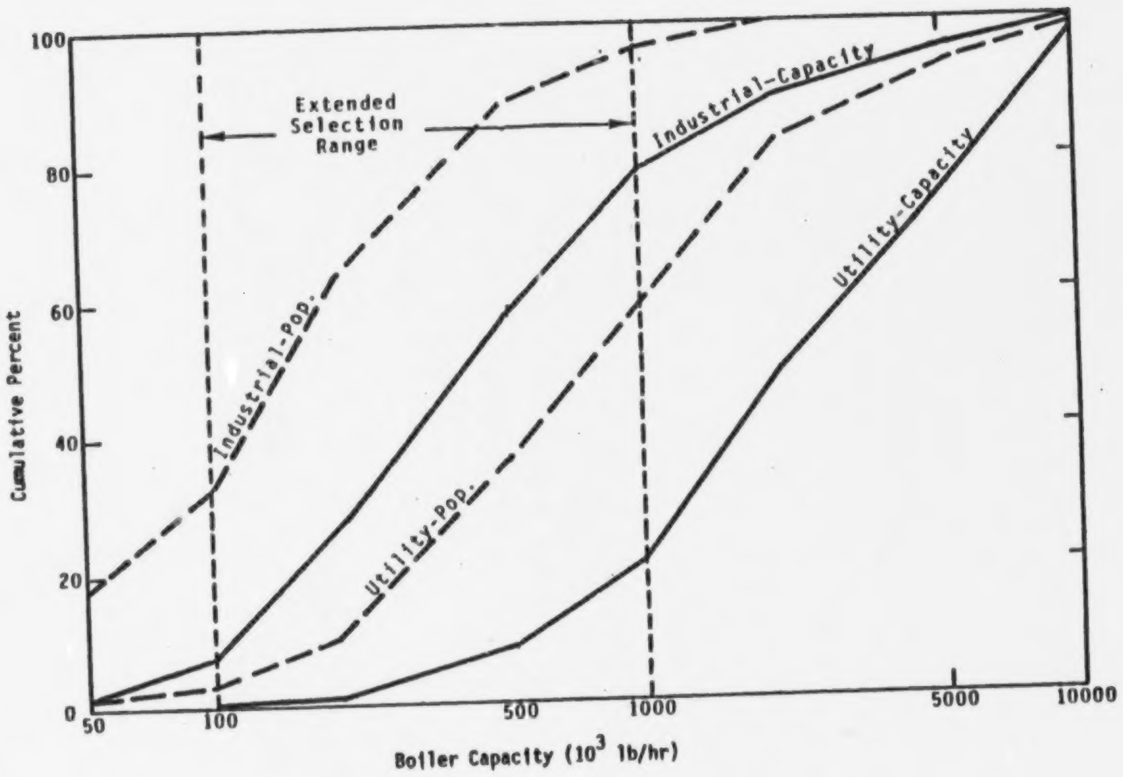


Figure 2-5. Capacity and population of industrial and utility boilers.

	Industrial Boilers	Utility Boilers
Population	65%	53%
Capacity	73%	20%

Based on these considerations, it was decided to extend the boilers considered for potential demonstration sites to include both industrial and utility units.

2.1.2 DMB Installation Considerations

The boilers selected as field evaluation sites must be compatible with the DMB concept. Specifically: (1) they must present minimal problems in retrofitting the burners with DMBs and (2) the potential for achieving low NO_x with the DMB concept on the host units must be representative of the existing and projected industrial boiler inventory. It should be noted that DMB installation in a new unit eliminates most of the complications discussed in this section. Section 6 presents an assessment of retrofit versus new application considerations.

The first consideration in the application of the DMB concept to an industrial boiler on a retrofit basis is the provision for supplying combustion air through the burner throat and the tertiary air ports. In conventional circular burners, all of the combustion air is supplied through the burner throat at high velocity. In the DMB, approximately 60 percent of the combustion air is supplied through the throat but at a considerably lower velocity than in circular burners. Depending on the burner velocities and geometry, the DMB throat diameter may exceed that of the conventional circular burner it replaces. In a retrofit installation, this would require replacing the water wall tubes in the vicinity of the throat. The complexity of this operation depends on the boiler construction (membrane wall or tangent tube), the burner to burner spacing and the tertiary port configuration. Each tertiary port requires a separate penetration through the water wall with associated tube bends. Those tubes which are bent lose their ability to carry vertical structural loads. This is a significant consideration since boilers in the size range of interest are typically supported from the top and the weight of the lower portion of the furnace is supported by the water wall tubes. In conventional burner installations without tertiary air ports, usually there are several straight tubes in the firing face to carry the structural loads. Depending on the tertiary air port configuration for the DMB, many of these tubes may need to be bent in a retrofit installation and the remainder of the straight tubes may be insufficient to support the lower furnace. This problem is compounded by burner arrays with several burners side by side. Such arrays require a larger number of tertiary ports in horizontal rows.

The locations of specific tertiary ports may present structural problems also. Usually, windbox trusses and buckstays are positioned between burners approximately where the tertiary air ports should be installed. If the tertiary air ports interfere with these structural members, it will be necessary to either reposition the tertiary air ports to a less optimum location or to modify the structural members. Since each boiler is constructed somewhat differently, the candidate demonstration sites must be evaluated independently. It should be noted that for new boiler designs the tertiary air port system will be included in the initial structural design and adequate lower furnace support will be provided.

The boilers selected as field evaluation sites must be representative of the existing and projected industrial boiler inventory in terms of their potential for low-NO_x emissions with the DMB. While the specific relationships between boiler design/operating parameters and NO_x emissions achievable with the DMB are not fully understood at present, the following parameters are important:

- Furnace Depth
- Furnace Thermal Environment
- Burner Array

Flame impingement on the furnace wall opposite the burners must be avoided due to the potential for ash buildup, corrosion and related problems. The DMB flame length can be adjusted by varying burner design parameters to achieve either short or long flames. Long flame DMB's tend to produce slightly lower NO_x emissions. However, the furnace depth of the units selected as demonstration sites should be representative of existing and projected industrial boilers. This corresponds to 20 to 24 ft depth and will require short flame DMBs.

The relationships between furnace thermal environment and NO_x emissions for coal fired burners are not fully understood. Correlations of field data suggest that NO_x emissions tend to increase with heat release per cooled surface area (such as BZLR) for commercial burners. Small scale data suggests that NO_x emissions from staged coal burning systems can be reduced by increasing the heat transfer from the fuel rich combustion zone. This heat transfer would be expected to reduce thermal NO_x formation. However, it also appears to reduce NO_x produced from fuel bound nitrogen. Several factors interact to determine heat transfer from the flame including the combustion air temperatures, the recirculation of combustion products in the furnace and the furnace cooled surface area.

For industrial and utility boilers in the size range of interest for this program, primary air temperatures are in the range of 130-180°F and windbox air temperatures are about 600°F at full load conditions. The primary air temperature is determined by the coal characteristics and the pulverizer operating parameters. The windbox air temperature is set by the boiler design and performance of the air heater. Thus, the DMB must be designed to accommodate these temperatures independent of their potential impacts on NO_x emissions.

Swirl stabilized flames such as those produced by the DMB entrain a substantial amount of combustion products. The temperature of the recirculated combustion products depends on the heat transfer from these products. For burners adjacent to water cooled walls, the temperature of the recirculated combustion products will be lower than for burners surrounded by other burners. Similarly, the radiant heat transfer from flames adjacent to cooled walls will be greater than from flames in the center of the burner array. Since DMB NO_x emissions are expected to decrease with flame temperature, burner arrays where each flame is adjacent to a cool furnace wall would be expected to result in lower NO_x emissions. For the host boilers, it would be desirable to test one burner array where all flames are adjacent to cooled walls (such as 2x2) and one more complex burner array (such 3x3).

The primary heat transfer from the flames is radiation to the water cooled walls. For large furnaces with several flames which effectively fill the lower furnace volume, the radiative heat transfer is related to the heat release per cooled surface area in the lower furnace and the BZLR. Thus, the BZLR for the demonstration sites should be representative of the range of industrial and utility boilers of interest. This is approximately 150 to 250 x 10^3 Btu/hr/ft^2.

In addition to the thermal effects discussed above, the burner configuration and spacing in the array will influence the potential for achieving low-NO_x emissions from the DMB. In burner arrays where several burners are spaced vertically, the combustion products from the lower flames are reprocessed through the upper flames. In addition, biased firing where the lower burners are operated at lower excess air than the upper burners provides a means of staging. Thus, it would be desirable to select field demonstration sites with different numbers of burners spaced vertically to evaluate this effect.

2.1.3 Host Boiler Selection Process

Foster Wheeler boilers in the range 100-1000 x 10^3 lb/hr steam raising capacity were surveyed to define potential host sites. The characteristics of approximately 50 boilers were reviewed and it was determined that 17 units had design and operating specifications appropriate for use as host boilers. These 17 units were divided into two groups:

- Units with 4 burners representing the smaller boiler sizes
- Units with up to 12 burners representing the larger boiler sizes

The design parameters and performance coal data for the 4-burner boilers are presented in Table 2-3. These 6 units are similar with only minor differences. Although there is some difference in both burner capacity 20-29 MW (70-100 x 10^6 Btu/hr) and burner zone liberation rate (BZLR) they are not considered to be significant. Two of the units fire sub-bituminous coal (heating value 8,000-9,000 Btu/lb) while the remainder fire bituminous coals (heating value about 13,000 Btu/lb).

The boiler design parameters and fuel characteristics for the larger industrial boilers are presented in Table 2-4. These units have considerably greater capacity and higher BZLR than the 4-burner units. However, several of the larger size units (specifically units 7-9, 11-14, and 16) have burners of approximately the same size as the 4-burner units (70-100 x 10^6 Btu/hr). Units 10, 15, and 17 are exceptions with larger burner capacities in the range of 125-140 x 10^6 Btu/hr. The variation in heating value of the coals for the larger units is not significant, although there is a 3/1 range in moisture and ash. There is also a wide range of sulfur between the various coals while the nitrogen is almost constant. Unit 17 is of particular interest since it fires a Utah coal similar to the baseline coal used in the DMB development program. A further advantage is the relatively small number of large burners (8) for a relatively large unit: 800 x 10^3 lb/hr. A disadvantage is that the unit has division walls.

Based on these considerations, it was decided that the selection would concentrate on identifying one 4-burner boiler and one 6-12 burner boiler as hosts. To prioritize the potential host, a rating system was developed as follows:

- Number of Burners - This factor affects both cost and relevance of the unit to modern designs.

Number of Burners	4	6-8	9-12
Weighting Factor	+2	+1	0

TABLE 2-3. CANDIDATE FOUR BURNER UNITS

	BOILER NUMBER					
	1	2	3	4	5	6
CAPACITY - MCR (10^3 LB/HR)	215	266	266	245	275	220
STEAM TEMPERATURE (^oF)	905	750	728	905	815	905
BZLR (10^3 BTU/HR FT^2)	136.7	184.6	179.7	186.7	217.2	161.7
BURNER LIBERATION (10^6 BTU/HR)	69.1	80.0	77.4	81.7	99.5	73.3
BURNER ARRAY: WIDE	2	2	2	2	2	2
HIGH	2	2	2	2	2	2
PERFORMANCE COAL (AS RECEIVED)						
HEATING VALUE (BTU/LB)	11,300	13,000	13,000	9,000	13,000	8,035
MOISTURE (%)	11.0	4.3	4.3	20.0	8.0	30.1
ASH (%)	9.5	11.5	11.5	8.0	9.0	6.0
CARBON (%)	62.8	73.5	73.5	51.9	70.3	46.0
HYDROGEN (%)	4.3	4.4	4.4	4.1	4.7	3.3
OXYGEN (%)	8.2	3.6	3.6	15.0	5.5	13.2
SULFUR (%)	3.0	1.2	1.2	0.2	1.1	0.5
NITROGEN (%)	1.2	1.5	1.5	0.8	1.4	0.9

Table 2-4. CANDIDATE SIX TO TWELVE BURNER UNITS

	BOILER NUMBER										
	7	8	9	10	11	12	13	14	15	16	17
CAPACITY - MCR (10^6 LB/HR)	400	893	925	860	700	625	425	600	845	385	800
STEAM TEMPERATURE (°F)	709	1000	1000	1000	1105	955	955	950	1005	905	1000
BZLR (10^3 BTU/HR FT^2)	229.9	253.7	283.7	221.3	223.4	205.9	258.7	291.2	191.5	198.1	225.0
BURNER LIBERATION (10^6 BTU/HR)	87.4	95.3	93.5	126.2	79.6	85.4	88.4	100.3	139.4	80.0	125.0
BURNER ARRAY: WIDE	3	4	6	4	6	3	3	4	2	3	4
HIGH	2	3	2	2	2	3	2	2	4	2	2
PERFORMANCE COAL (AS RECEIVED)											
HEATING VALUE (BTU/LB)	14,100	10,200	10,200	10,400	11,200	11,600	11,600	13,300	12,600	12,700	9,200
MOISTURE (%)	4.1	10.0	10.0	13.0	10.4	8.9	8.9	5.0	6.5	6.0	22.1
ASH (%)	5.1	14.0	14.0	12.2	11.3	10.3	10.3	8.6	6.5	7.9	9.2
CARBON (%)	80.3	42.9	42.9	39.6	61.2	64.5	64.5	75.0	68.5	70.3	52.9
HYDROGEN (%)	4.4				4.8	4.4	4.4	4.3	5.1	5.0	4.1
OXYGEN (%)	4.2				7.6	8.9	8.9	4.1	11.5	6.8	9.5
SULFUR (%)	0.7				3.6	1.9	1.9	1.9	0.7	2.6	0.9
NITROGEN (%)	1.2				1.1	1.1	1.1	1.1	1.2	1.4	1.3
VOLATILES (%)		33.1	33.1	35.2							

PROXIMATE ANALYSIS

BLENDED FUEL

- Burner Configuration - This factor affects relevance to modern design and complexity of installing a tertiary air system. Some configurations are no longer used and are therefore not representative of modern steam generator designs.

Configuration (w x h)	2x2	3x2	2x4	3x3	4x2	6x2
Weighting Factor	+2	+2	+1	+0	-1	-2

- Burner Design - Although pre-NSPS burners were similar they represent an evolutionary improvement over the course of about twenty years (from about 1945 to 1965; pre-war designs are not included). Later designs are more representative of modern pre-NSPS industrial and utility burners which differ mainly in capacity and range from 50-300 x 10^6 Btu/hr. These burner evolutionary design differences can be best expressed in terms of geometrical, flow and velocity relationships. These relationships have been evaluated and are implicitly included in the summary comparison table. However, since these burner parameters are considered proprietary, they are not explicitly presented.

- Burner Liberation - Burner liberation depends on the unit capacity, the number of pulverizers required and the pulverizer redundancy specifications. Industrial boilers are typically in the range of 50-125 x 10^6 Btu/hr per burner; large utility boilers are typically up to 300 x 10^6 Btu/hr per burner. The weighting factor was chosen to favor smaller burners for units below 400 x 10^3 lb/hr capacity and larger burners for units over 400 x 10^3 lb/hr.

Unit Capacity (lb/hr)	<400,000	1	>400,000	1
Burner Capacity (10^6 Btu/hr)	<100	>100	<100	>100
Weighting Factor	+2	0	0	+2

- **Windbox Configuration** - The simple common windbox lends itself to retrofit of the tertiary air port burner. Some older units have compartmented windboxes or coal conduits inside the windbox which would complicate low NO_x burner installation.

Windbox Configuration	Common	Divided
Weighting Factors	+2	-2

- **Division Walls** - Full division walls were used on may pre-NSPS steam generators, however, they are seldom used on modern units. Partial (upper furnace) division walls or platens are usually used. It is therefore preferable not to have any full division in the host boiler.

Number of Full Div. Walls	0	1	2
Weighting Factor	+2	+1	-1

- **Retrofit Capability for Tertiary Air System** - The tertiary air system may have a major impact on the structural supports in the windbox and structural strength of the firing wall. The impact of the tertiary air system is related to the number of burners along with width of the firing wall. A wide unit may be unable to accept a large number of tertiary air ports without reducing the structural strength of the wall: an alternate tertiary air system would then have to be evaluated.

Number of Burner Wide	2	3	4	5
Weighting Factor	+3	+2	0	-3

Table 2-5 lists the weighting factors applied to each potential host boiler and Table 2-6 shows the relative rankings. It should be emphasized that all of the potential host units are acceptable as host sites regardless of ranking. However, the top ranked units are more desirable in that their selection would be most representative of the existing and projected industrial boiler population or would result in lower program costs, etc.

The small unit capacity range is 215-275 x 10^3 lb/hr and the units are of similar overall design, firing configuration and vintage. The primary

TABLE 2-5. WEIGHTING FACTOR SUMMARY

Initial Small Boiler Units

	Unit No.					
Weighting Factor	1	2	3	4	5	6
No. of Burners	+2	+2	+2	+2	+2	+2
Burner Configuration	+2	+2	+2	+2	+2	+2
Burner Design	-1	+1	+2	-2	-1	-3
Burner Liberation	+2	+2	+2	+2	+2	+2
Windbox Configuration	+2	+2	+2	+2	+2	+2
Division Walls	+2	+2	+2	+2	+2	+2
Tertiary Retrofit Capability	+3	+3	+3	+3	+3	+3
TOTAL	+12	+14	+15	+11	+12	+10

Second Large Boiler Units

	Unit No.										
Weighting Factor	7	8	9	10	11	12	13	14	15	16	17
No. of Burners	+1	0	0	+1	0	0	+1	+1	+1	+1	+1
Burner Configuration	+2	0	-2	-1	-2	0	+2	-1	+1	+2	-1
Burner Design	-1	-1	-1	-3	0	0	-1	-2	+1	-1	+1
Burner Liberation	0	0	0	+2	0	0	0	+2	+2	0	+2
Windbox Configuration	+2	-2	-2	+2	-2	+2	+2	-2	+2	+2	-2
Division Walls	+2	+1	+1	+1	+2	+2	+2	+2	+1	+2	+1
Tertiary Retrofit Capability	+2	0	-3	0	-3	+2	+2	0	+3	+2	0
TOTAL	+8	-2	-7	+2	-5	+6	+8	0	+11	+8	+2

TABLE 2-6. PRIORITIZED LIST OF UNITS

A. Four-Burner Units

Rank	Unit No.	Location
I	3	South Carolina
II	2	Virginia
III	5	Michigan
III	1	Illinois
IV	4	Alaska
V	6	Wyoming

B. Six to Twelve-Burner Units

Rank	Unit No.	Location
I	15	Nevada
II	16	Iowa
II	13	Ohio
II	7	Virginia
III	12	Ohio
IV	10	Minnesota
IV	17	Minnesota
V	14	Pennsylvania
VI	8	Kentucky
VII	11	Indiana
VIII	9	Kentucky

parameter affecting the ranking is the fuel composition as reflected by burner design.

The larger unit capacity range is 385-925 x 10^3 lb/hr. There are significant differences in boiler designs, configurations and vintage. The relative ranking indicate which units are preferable as hosts. The lower four units (ranked V-VIII) are least preferable because they are burner and boiler designs which have not been manufactured for over 20 years. The ages of these units are close to their design life and the units would be replaced with newer designs which have little in common with existing units. The higher ranked units are preferable from both design and ease of retrofit capability view points. Note that units, 7, 13, and 16 are of equal rank as are units 10, and 17 (ranked II and IV respectively).

Foster Wheeler Sales and Services representatives made the initial contacts with the boiler owners/operators by presenting an outline of the program and possible contractual arrangements. Where a favorable response was obtained, meetings were held to detail the program's scope and to solicit an agreement to participate. The responses to the initial contacts with the smaller units are summarized in Table 2-7. Among the 4-burner units, four were eliminated due to insufficient steam demand or reserved capacity or remote location. Unit 1 was Western Illinois Power Cooperative's (WIPCO) Pearl Station Unit 1. WIPCO agreed to participate in the program and thus this unit was selected as the initial demonstration site. Since the WIPCO unit was ranked Third, no contact was made with the remaining unit ranked Fifth.

The responses to the initial contacts with larger units are summarized in Table 2-8. The top eight units were contacted (rank 1 to 5). Among these, three either declined participation or failed to respond. Three others were eliminated due to removal of coal handling equipment, unacceptable unit operation or currently out of service. Units 2 and 17 agreed to participate subject to final negotiation. However, these negotiations were never consummated since the 2nd demonstration was cancelled.

TABLE 2-7. INITIAL SMALL BOILER CANDIDATES

Prioritization Rank	Reference Number	Capacity x 10^3 lb Steam/hr	Location	Status of Discussions/Negotiations
1	3	266	South Carolina	Eliminated due to Insufficient Reserve Capacity
2	2	266	Virginia	Eliminated due to Insufficient Reserve Capacity
3	5	275	Michigan	Eliminated due to Insufficient Steam Demand (Unit Operated only at Part Load)
③	1	215	Illinois	Agreed to Participate Subject to Final Negotiations
4	4	245	Alaska	Eliminated Due to Location
5	6	220	Wyoming	Not Contacted

TABLE 2-8. LARGE BOILER CANDIDATES

Prioritization Rank	Reference Number	Capacity x 10^3 lb Steam/hr	Location	Status of Discussions/Negotiations
1	15	845	Nevada	Eliminated, Declined Participation
②	16	385	Iowa	Agreed to Participate Subject to Final Negotiations
2	13	425	Ohio	No Response
2	7	400	Virginia	Eliminated, Coal Handling Equipment has been Removed
3	12	625	Ohio	No Response
④	17	800	Minnesota	Agreed to Participate Subject to Final Negotiations
4	10	860	Minnesota	Eliminated, Unit Operation Unacceptable
5	14	600	Pennsylvania	Eliminated, No Longer Operating
6	8	853	Kentucky	Lowest Priority Units - Not Contacted
7	11	700	Indiana	
8	9	925	Kentucky	

2.2 Host Boiler Characteristics

The host boiler, WIPCO's Pearl Station Unit 1, is a small utility boiler with a steam raising capacity of 215 x 10^3 lb/hr (880 psig, 905°F). At this capacity, 20 MW of electrical power is produced. WIPCO is a rural cooperative utility and purchases most of its electrical power. The remainder is generated by Pearl Station Unit 1 which is the only steam-electric unit. Additional gas turbine and diesel units are available at Pearl Station and elsewhere. However, they are operated only occasionally since purchased power is usually less expensive. Pearl Station is base loaded and operates at full load or higher for a majority of the time. Peak power production is 21.5 MW limited by turbine capacity.

The design and operating characteristics of Pearl Station Unit 1 are listed in Table 2-9. Figure 2-6 is a cross-sectional side view of the unit. It was erected in 1965 by Foster Wheeler and is front wall fired with four Intervane Burners in a 2x2 array. Two Foster Wheeler vertical spindle pulverizers with integral classifiers are used, one for each burner row. Primary air (PA) is supplied to each pulverizer by individual PA fans. The unit is forced draft and (pressurized furnace) is equipped with a regenerative air heater. The primary emission control system is a multiclone. However, this was incapable of meeting local particulate emission limits and a wet scrubber was retrofitted in series. The wet scrubber has an induced draft fan which provides a pressure rise to offset the scrubber pressure drop plus a small reserve. Thus, operating the scrubber reduces the furnace pressure somewhat but the furnace pressure is still considerably above ambient pressure.

Figure 2-7 shows the load schedule (i.e., variation of operating conditions with load) based on tests conducted prior to this program. The primary temperature and stoichiometry were measured with only one mill in service. However, the results are typical of two mill operation also. The primary air flow rate is essentially constant, increasing about 15 percent as the load is increased from 50 to 80 x 10^6 Btu/hr per burner. This results in a slight decrease in primary stoichiometry as load increases. The primary

TABLE 2-9. INITIAL INDUSTRIAL BOILER FIELD SITE CHARACTERISTICS

Characteristic		Value
Boiler/Furnace		
Boiler Capacity	MCR	215 x 10^3 lb/hr
	Peak	245 x 10^3 lb/hr
Furnace Depth		20.6 ft
Furnace Width		16.4 ft
Firing Configuration		Single Wall
Burner Capacity	MCR	69 x 10^6 Btu/hr
	Peak	80 x 10^6 Btu/hr
Current Burners	Type	Intervane
	Throat Diameter	24 in.
Burner Array, Wide x High		2 x 2
Burner Spacing:	Horizontal	6.0 ft
	Vertical	6.5 ft
Fuel Supply System		
Coal Type		Bituminous
Mills:	Type	MB
	Number	2
Primary Stoichiometry at:	MCR	16% T.A.
Primary Temperature		155°F
Air Supply System		
Air Heater Type		Regenerative
Design Point Excess Air at:	MCR	18%
Windbox Temperature at:	MCR	510°F
Burner Pressure Drop (Normal)		3.5 in. H_2O
Windbox Depth		52 in.

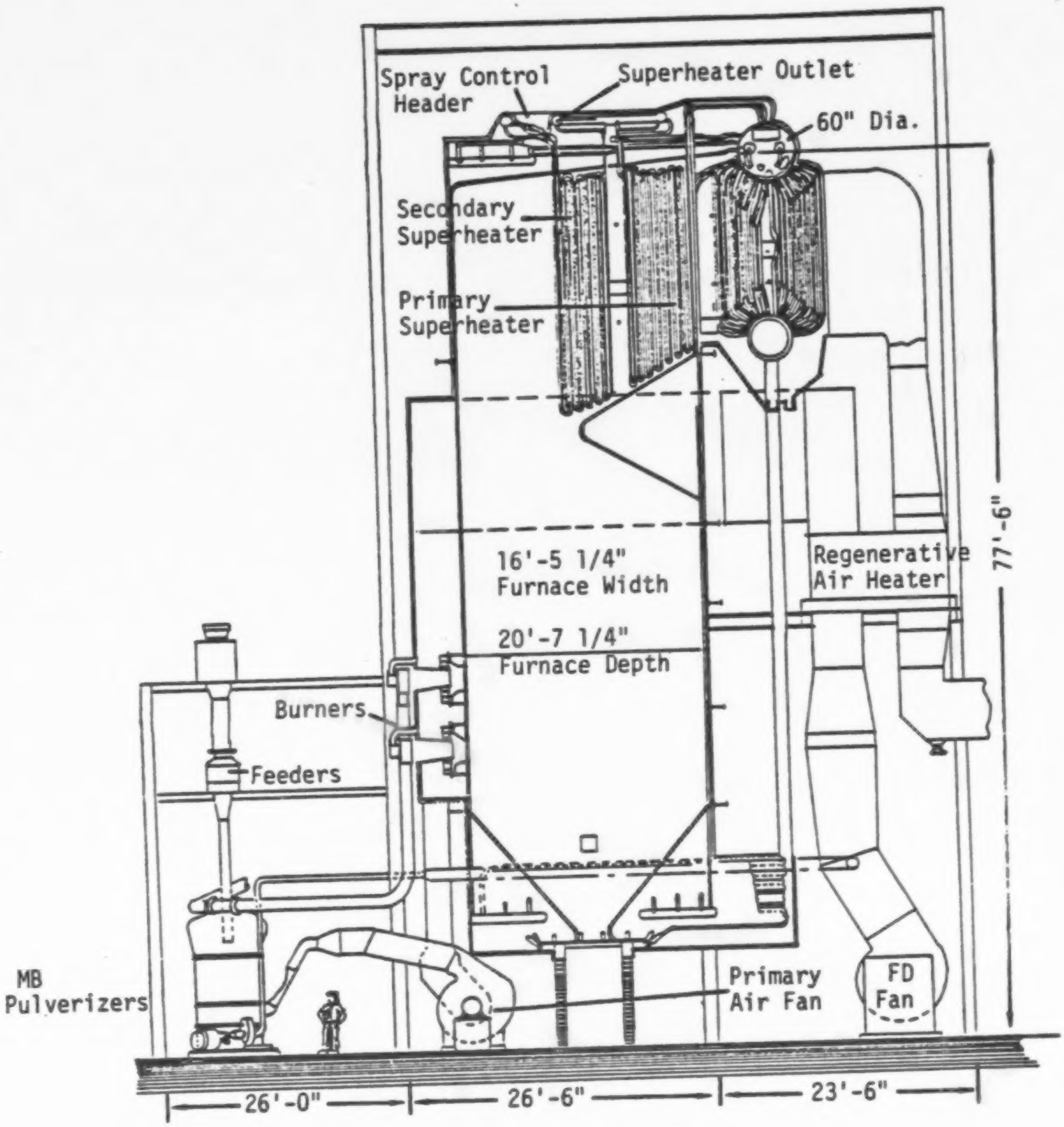

Spray Control Header
Superheater Outlet
60" Dia.
Secondary Superheater
Primary Superheater
16'-5 1/4" Furnace Width
20'-7 1/4" Furnace Depth
Regenerative Air Heater
77'-6"
Burners
Feeders
MB Pulverizers
Primary Air Fan
FD Fan
26'-0"
26'-6"
23'-6"

Figure 2-6. Cross-section of initial industrial boiler.

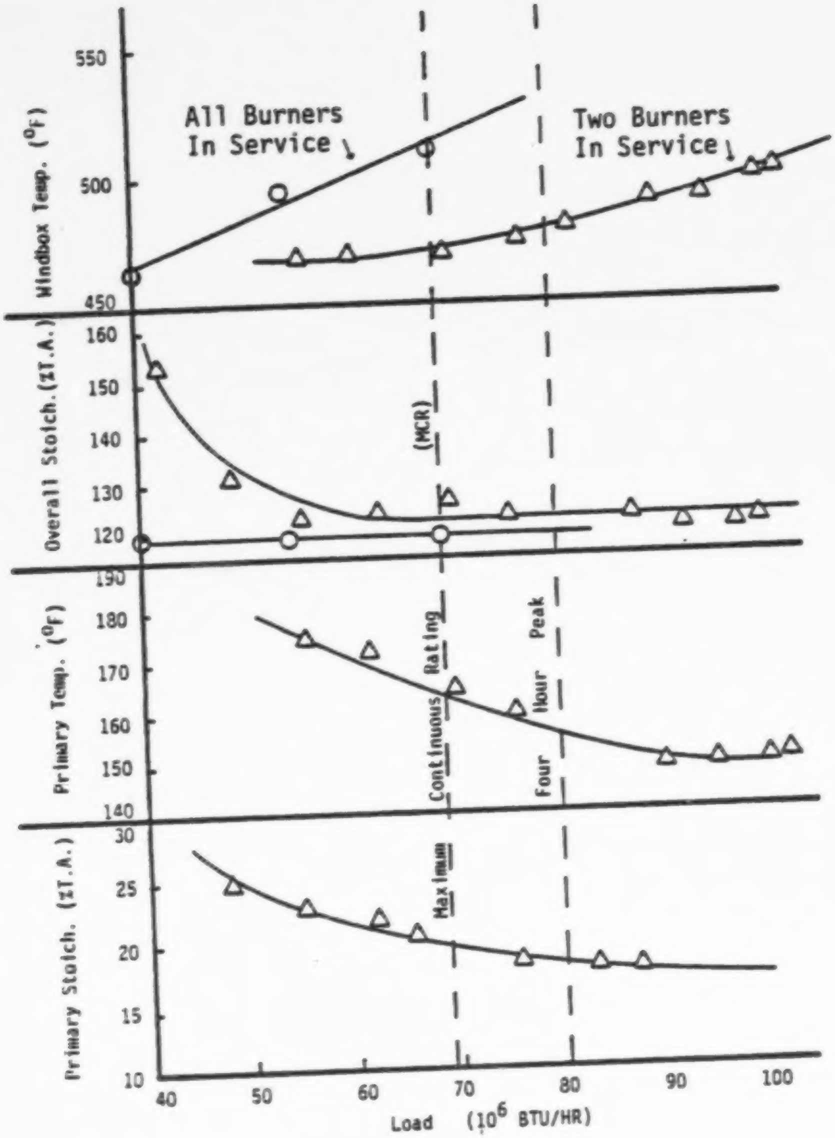


Figure 2-7. Burner load schedule for initial industrial boiler.

temperature is usually maintained in the range of 150 to 160°F, but in these data it was allowed to increase to 170°F.

The excess air levels for this unit are shown for two conditions: all burners in services at the boiler design point and two burners in services. This unit uses spray attemperation to control steam temperature and an excess air level of 18 percent allows design point steam temperature to be maintained down to about half of maximum continuous rating. With two burners out of service, excess air is increased at low load to maintain steam temperature. The windbox temperature depends on the performance of the regenerative air heater which is related to the boiler load and excess air.

WIPCO has no long term coal contract. Coal is purchased on the spot market and its characteristics may vary substantially. The coals are selected based on lowest delivered price per unit heating value ($\$/10^6$ Btu) for high volatile bituminous coals with a maximum sulfur content of 4.0 percent. Coals from the Three States Trucking Mine in Indiana has been fired for much of the time. Its characteristics are listed in Table 2-10.

2.3 Boiler Baseline Evaluation

The objective of the boiler baseline evaluation was to determine the performance of the host boiler with the original equipment burners. The data were used to establish the operating requirements for the DMBs and to determine the baseline boiler performance and emissions for assessment of the net change due to retrofitting the DMBs. The specific goals were to evaluate the following:

1. Normal full load operating conditions, performance and emissions.

2. Typical duty cycle and operating ranges as well as operating limits.

3. Effects of operating parameters on emissions.

TABLE 2-10. TYPICAL COAL FIRED AT WIPCO'S PEARL STATION UNIT 1

	As Received	Dry Basis
Proximate Analysis		
% Moisture	13.03	
% Ash	10.14	11.66
% Volatile	36.00	41.49
% Fixed Carbon	40.75	46.85
	100.00	100.00
Btu	11,216	12,896
% Sulfur	2.87	3.30
% Alk. as Na_2O	0.19	0.22
Sulfur Forms		
% Pyritic Sulfur	1.74	2.00
% Sulfate Sulfur	0.03	0.03
% Organic Sulfur	1.10	1.27
% Total Sulfur	2.87	3.30
Water Soluble Alkalies		
% Na_2O	0.006	0.007
% K_2O	0.003	0.004
	Reducing	Oxidizing
Fusion Temperature of Ash		
Initial Deformation	2080°F	2370°F
Softening (H = W)	2140°F	2410°F
Softening (H = ½W)	2190°F	2450°F
H = cone height		
W = cone width		
Fluid	2320°F	2550°F

Hardgrove Grindability Index = 69.0
(HGI @ 9.47% moisture)

	As Received	Dry Basis
Ultimate Analysis		
Moisture	13.03	
Carbon	61.30	70.40
Hydrogen	4.36	5.01
Nitrogen	1.30	1.49
Chlorine	0.03	0.04
Sulfur	2.87	3.30
Ash	10.14	11.66
Oxygen (diff)	6.97	8.02
	100.00	100.00

	% Weight Ignited Basis
Mineral Analysis	
Phos. pentoxide, P_2O_5	0.15
Silica, SiO_2	44.03
Ferric oxide, Fe_2O_3	26.85
Alumina, Al_2O_3	21.49
Titania, TiO_2	1.02
Lime, CaO	1.33
Magnesia, MgO	0.77
Sulfur trioxide, SO_3	0.50
Potassium oxide, K_2O	2.39
Sodium oxide, Na_2O	0.31
Undetermined	1.16
	100.00

Base: Acid Ratio = 0.48
Silica Value = 60.33
T250 = 2340°F

Estimated Viscosity at Critical Viscosity Temperature of 2390°F = 125 Poise

4. Potential for NO_x reduction with combustion modification but without component changes.

The baseline tests were conducted in the following four test series:

1. Optimization test
2. 30 day baseline test
3. Effluent stream analysis
4. Thermal efficiency test

The optimization tests involved adjustment of burner/boiler operating conditions and settings over wide ranges to establish their impact on burner performance and NO_x emissions and to define the settings which minimize NO_x emissions. These tests were conducted in the summer of 1980. A Foster Wheeler service engineer was present for the duration of the tests to ensure that the operating conditions were representative of normal burner/boiler performance. EER coordinated the tests and made all measurements.

The 30-day baseline test was conducted immediately following the optimization tests. This involved monitoring burner/boiler performance while the operators adjusted the burners and operated the unit over the normal duty cycle.

The effluent stream analysis and thermal efficiency tests were conducted in March, 1981 immediately prior to the DMB installation. The effluent stream analysis was an EPA Level 1 Environmental Assessment and was conducted by ACUREX Corporation. During the Level 1 test, EER monitored performance in the same manner as during the 30-day test. Although the Level 1 test was completed, the data were not useful due to extensive quality assurance problems. The thermal efficiency test was conducted by Foster Wheeler and the results are discussed in Section 4.

The following subsections discuss normal full load operation, the operating range of the unit, the effects of operating conditions on emissions and the potential for reducing NO_x emissions via burner adjustments.

2.3.1 Normal Full Load Operation

Boiler emissions were measured at the normal full load operating conditions as part of the Optimization Tests to establish the baseline emissions. Nominal operating conditions are defined as the following:

1. Load - maximum continuous rating (20 MW).
2. Excess Air - design point (18 percent).
3. Other - conditions normally set by operating personnel.

Table 2-11 summarizes the emissions at nominal conditions. The table also shows average emissions during the 30-day Baseline Test and during the Effluent Stream Analysis for comparison. During the 30-day Baseline Test, the boiler operating conditions were selected by the operators. During the Effluent Stream Analysis, the boiler was operated at nominal operating conditions. Boiler operating conditions were similar during each of the three test series. The average load measured during the 30-day Test was 18.5 MW showing that the unit primarily operates at or near full load. The excess air was slightly higher during the 30-day Baseline Test and the Effluent Stream Analysis, but this higher excess air did not affect the boiler emissions significantly. Combustion efficiency as measured by carbon utilization was approximately constant for all three test series. Boiler efficiency results are presented in Section 4.

As shown in Table 2-11, NO_x and CO emissions during the 30-day baseline test and effluent stream analysis were very close to the baseline emissions measured during the Optimization Tests. SO_2, SO_3, and particulate emissions varied due to changes in the sulfur and ash contents of the coal. Hydrocarbon, HCN, and NH_3 emissions were all very low. The low CO and hydrocarbon concentrations are comparable to those observed on other Foster Wheeler boilers of similar design.

Results of the fly ash particle size distribution analyses during the three test series are shown in Figure 2-8. The particle size tests were conducted at nominal conditions during the Optimization Tests and Effluent

TABLE 2-11. NOMINAL BOILER OPERATING CONDITIONS AND EMISSIONS

	Test Series and Dates		
	Optimization Tests (6/30/80 to 7/12/80)	30-Day Baseline Test Average (7/15/80 to 8/17/80)	Effluent Stream Analysis (3/22/81 to 3/27/81)
Boiler Operating Conditions:			
Load (MW_e)	20.3	18.5	19.7
Excess Air (%)	18.9	20.5	23.2
Carbon Utilization (%)	99.54	99.36	99.67
Emissions:			
NO_x @ 0% O_2 (ppm)	826	847	807
CO @ 0% O_2 (ppm)	41	37	32
SO_2 @ 0% O_2 (ppm)	3369	3299	4289
SO_3 @ 0% O_2 (ppm)	22	25	35
CO_2 @ 0% O_2 (%)	18.9	18.5	18.1
O_2 @ 0% O_2 (%)	3.4	3.6	4.0
Hydrocarbons@ 0%O_2(ppm)	1	1	4
Total Particulate @ 0%O_2* (gr/scf)	7.98	5.93	9.83
Particulate/ash in coal (ratio)	0.965	0.828	0.812
HCN @ 0% O_2 (ppm)	Not Measured	Not Measured	< 1
NH_3 @ 0% O_2 (ppm)			< 1

* 1.0 gr/SCF = 2.29 g/m^3

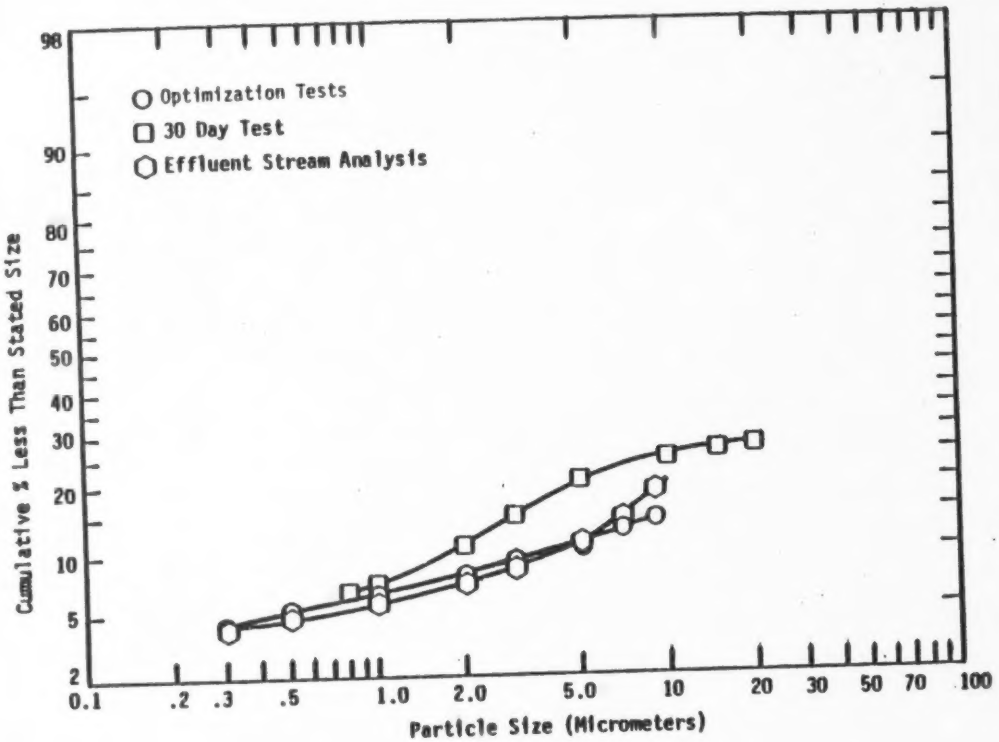


Figure 2-8. Results of particle size distribution analysis.

Stream Analysis. Tests conducted during the 30-day Baseline Test were at similar conditions, with load varying from 18 to 20 MW and excess air varying from 18 to 23 percent. The results of the size distribution measurements are very similar for each test series.

The burner register settings at nominal conditions during the Optimization Tests are shown in Figure 2-9. The burner core air valves were open fully. The burner adjustments were similar during the 30-day Baseline Test and Effluent Stream Analysis. As shown in Figure 2-9 the upper registers were more open than the lower registers. These settings were found to produce the most uniform flame shapes on all four burners at nominal operating conditions. At nominal conditions, the flames from all burners stabilized close to the throat exit (within 2 in.). The furnace was filled with luminous combustion products, making it difficult to delineate specific flame boundaries. The flames did not appear to impinge on the rear wall or on the side walls adjacent to Burners 1 and 3 (north wall). However, the flame from Burner 4 was observed to roll along the adjacent side wall (south wall). The side wall adjacent to Burner 2 could not be observed due to the location of the observation port.

To determine combustion conditions within the furnace, O_2 and CO concentrations were measured at the furnace walls using sample taps installed prior to the baseline testing. Average gas concentrations with normal full load operation during the Optimization Tests are shown in Table 2-12. These measurements confirm that reducing conditions (low oxygen and high CO) existed in the areas adjacent to Burners 2 and 4. This corresponds to the areas where the flame was observed to contact the furnace wall. Measurements of the same gases at the twelve probe locations upstream of the air heater resulted in essentially uniform results. Thus, the variations in gas concentrations exiting the burner zone are effectively smoothed out in the upper furnace and convective pass. Various register adjustments proved unsuccessful in producing symmetrical flames and Foster Wheeler has advised that this condition is unusual. Similar furnace wall concentrations were noted throughout the 30-day Baseline Test. However, during the Effluent Stream Analysis, O_2 and CO concentrations on the south wall were similar to

Note: Burner Locations as Viewed from Rear of Windbox.

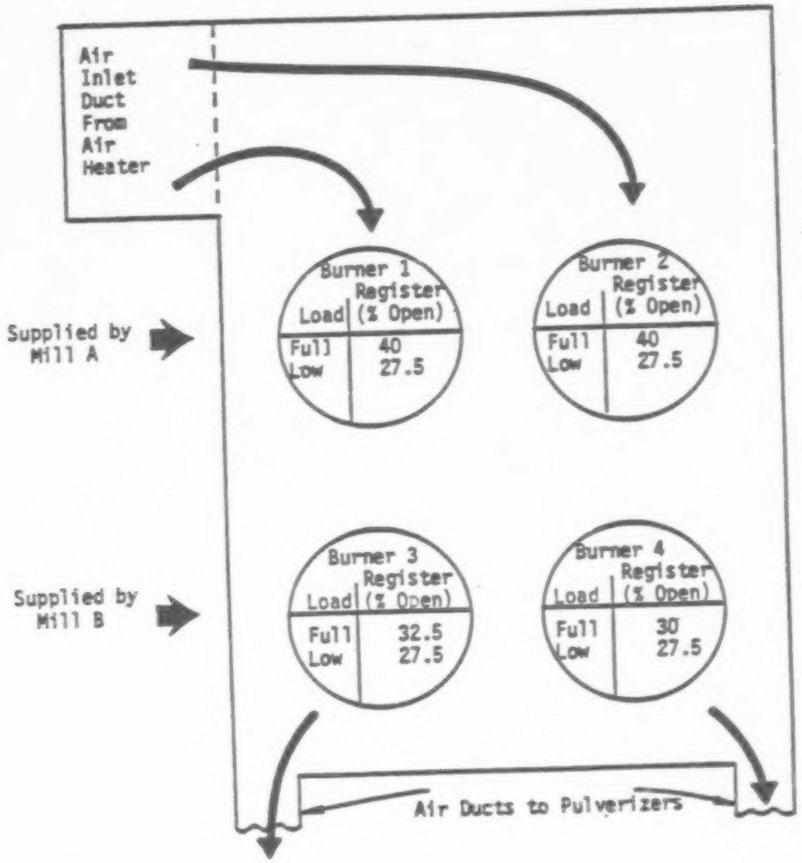

Air Inlet Duct From Air Heater
Supplied by Mill A
Supplied by Mill B
Burner 1
Load | Register (% Open)
Full 40
Low 27.5
Burner 2
Load | Register (% Open)
Full 40
Low 27.5
Burner 3
Load | Register (% Open)
Full 32.5
Low 27.5
Burner 4
Load | Register (% Open)
Full 30
Low 27.5
Air Ducts to Pulverizers

Figure 2-9. Normal register adjustment.

TABLE 2-12. FURNACE WALL GAS COMPOSITION DURING THE OPTIMIZATION TESTS

Species	Furnace Walls		
	Adjacent to Burners 1 & 3 (North Wall)	Adjacent to Burners 2 & 4 (South Wall)	Rear Wall
O_2 as measured (%)	2.4	0.2	3.0
CO @ 0% O_2 (ppm)	202	>2000	202

TABLE 2-13. FURNACE WALL GAS COMPOSITION DURING EFFLUENT STREAM ANALYSIS TEST

Species	Furnace Walls		
	Adjacent to Burners 1 & 3 (North Wall)	Adjacent to Burners 2 & 4 (South Wall)	Rear Wall
O_2 as measured (%)	2.7	2.4	3.0
CO @ 0% O_2 (ppm)	434	138	84

those on the other walls, as shown in Table 2-13, although some flame impingement was noted. This change in gas concentrations suggests that the cause of the reducing conditions noted at the south wall was related to a change in the performance of the fuel or firing system between the 30-day Baseline Test and Effluent Stream Analysis. Changes in coal pulverizer performance could have such an effect due to non-uniform distribution of coal to the burners.

2.3.2 Operating Range

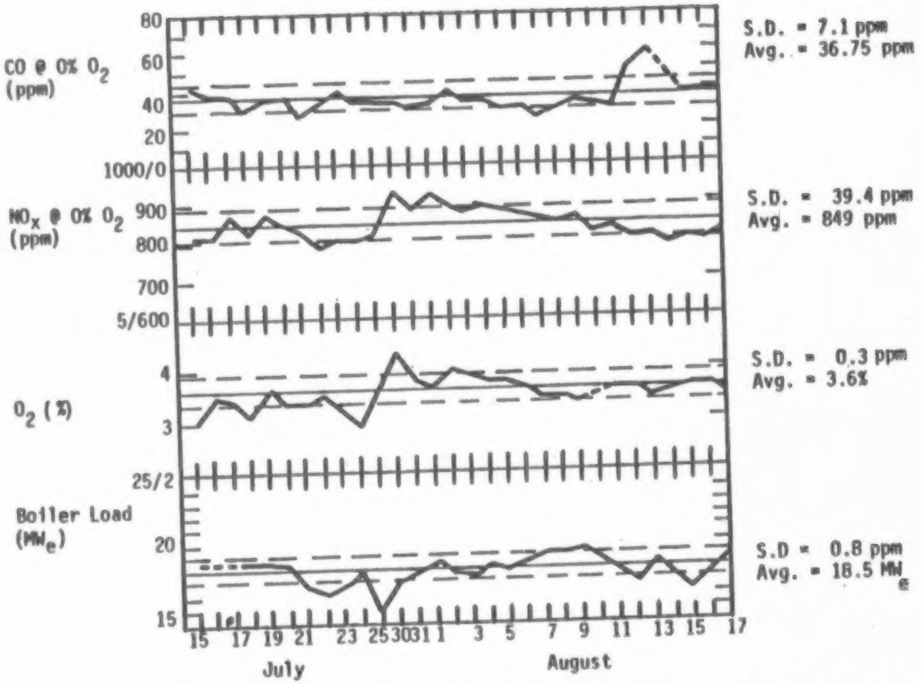
A key objective of this demonstration program was to provide information on the ability of the low NO_x burners to operate satisfactorily over a range of boiler operating conditions comparable to the original equipment burners. Therefore, as part of the Optimization Tests, boiler operating conditions (load, excess air, and burner adjustments) were varied to determine the range of operation achievable by the original equipment burners. Following the Optimization tests, the boiler was operated over the normal duty cycle during the 30-day Baseline Test to evaluate the range of operating conditions typically required by the boiler operators.

Table 2-14 shows the range of operating conditions used by the boiler operators during the 30-day Baseline Test compared to the range achieved during the Optimization Tests. The WIPCO unit is primarily base loaded and the boiler normally operates over a limited range of conditions. Changes in operating conditions during the 30-day Baseline Test were related to changing load requirements. At reduced loads, the boiler is operated typically at high excess air and with the burner registers closed from the nominal full load conditions.

Figure 2-10 shows the emissions and load history for the 30-day Baseline Test. The values plotted are daily averages. The overall averages and standard deviations based on the daily averages are listed also. During this period, the unit operated at 20 MW (full load) or greater during the day with reductions to about 15 to 18 MW at night. The average load for the period was 18.5 MW. There was a short unscheduled outage during the test period due

TABLE 2-14. RANGE OF OPERATING CONDITIONS ACHIEVED DURING THE OPTIMIZATION TESTS COMPARED TO THE 30-DAY BASELINE TEST.

Operating Variable	Range of Operation	
	30-Day Baseline Test	OPTIMIZATION TESTS
Load (% of Full Load)	75 to 101	66.5 to 105.5
Excess Air (%)	13.5 to 30	13.3 to 31.5
Register Position (% Open from Normal)	-10 to 0	-10 to +5
Core Air (% Open)	100	55.6 to 100
Mill Bias (% Bias)	0	0 to 26



Note: Boiler shut down from July 25 to July 30, 1980 for unscheduled outage unrelated to 30 day test.

Figure 2-10. 30-day baseline test results.

to causes unrelated to the test. This is responsible for the relatively low load on July 25. On August 13, a slight peak in CO occurred immediately prior to a CO instrument failure. It is possible that this peak was due to a problem with the instrument but, in any case, the CO emissions were always quite low, less than 80 ppm. Except for these occurrences, the performance over the 30-day period was relatively constant.

During the Optimization Tests, it was possible to operate the boiler over a load range of 13 to 21 MW. The maximum load was limited by steam condenser capacity. The minimum load was determined by increasing flame instability with decreasing load. The reasons for the instability are not known but may be due to the inability of the coal feeders to operate at low feed rates. The feeders at WIPCO are oversized. At loads less than 15 MW the operators have observed that the feed rate can vary erratically.

The minimum excess air achieved during the Optimization Tests was specified by the WIPCO management based on their experience that the flame may become unstable at low excess air. However, at the minimum excess air (13.3 percent) operating condition the flames appeared stable and CO levels did not increase. This indicates that lower excess air levels may have been possible. The maximum excess air (31.5 percent) allowed an accurate evaluation of the slope of the NO_x versus excess air curve without reducing boiler efficiency significantly. The core air valve adjustment from 90^o open (nominal condition) to 50^o open drew the flame into the throat approximately 2 in., therefore limiting further core air valve closing. The range of mill bias was limited by minimum feeder speed on the mill supplying the upper burners. The range of variation in register positions from the baseline was controlled by the flame stand-off distance as indicated by the main flame scanner. Opening the registers more than five percent from baseline caused the base of the flame to move out into the furnace (increased flame stand-off), resulting in a loss-of-flame indication. Closing the registers more than five percent from baseline drew the flame back into the throat. Operation at this condition is normally avoided due to the potential for slag formation in the burner exit and/or coking or overheating of the nozzle.

In addition to these operating conditions, the feasibility of operation with only one mill (two burners) in service was tested. It was found that the WIPCO boiler could not be operated with only one mill in service without supplementary oil firing for flame stability. Attempts to shut-off the supplementary oil firing with two burners in service resulted in a loss-of-flame indication on the flame scanning system. FW service personnel have observed the flames visually and determined that the problem is caused by the main flame scanner being located within the core region. This is not recommended by FW. The scanner was installed by the scanner supplier. Under some conditions the coal skirt formed by the annular nozzle shades the scanner so that a false loss of flame signal is received and the mill is tripped. This has occurred in the presence of FW personnel even though a satisfactory flame was observed visually.

2.3.3 Effects of Operating Conditions on Emissions

Operating conditions and burner adjustments evaluated during the optimization tests included load (firing rate), excess air, core air valve settings and register positions. The range of emissions measured during the optimization tests is listed in Table 2-15.

Tests of other commercial burners have shown that the relationships between NO_x emissions, firing rate and excess air are approximately linear over the normal operating ranges. Consequently, data from the optimization tests with the nominal core air valve and register settings was fitted to a linear relationship using a least squares technique. The result was the following correlation:

$$NO_x \ @ \ 0\% \ O_2 \ (\text{ppm}) = 2.30 \times (\% \text{ Full Load}) + 9.30 \times (\% \text{ Excess Air}) + 427.7$$

Figure 2-11 shows the relationship between NO_x emissions and firing rate (load) at constant excess air. All data points were corrected to the design point excess air (18 percent) using the correlation. All the data lie within a band of ±25 ppm except for the point at 67 percent load which is about 75

TABLE 2-15. RANGE OF GASEOUS EMISSIONS

Species	Range of Emissions Concentration @ 0% O_2, dry
O_2 (%)	2.5 to 5.1
NO_x (ppm)	670 to 955
CO (ppm)	30 to 53
CO_2 (%)	17.2 to 18.8
SO_2 (ppm)	3043 to 3805
HC (ppm)	0 to 3

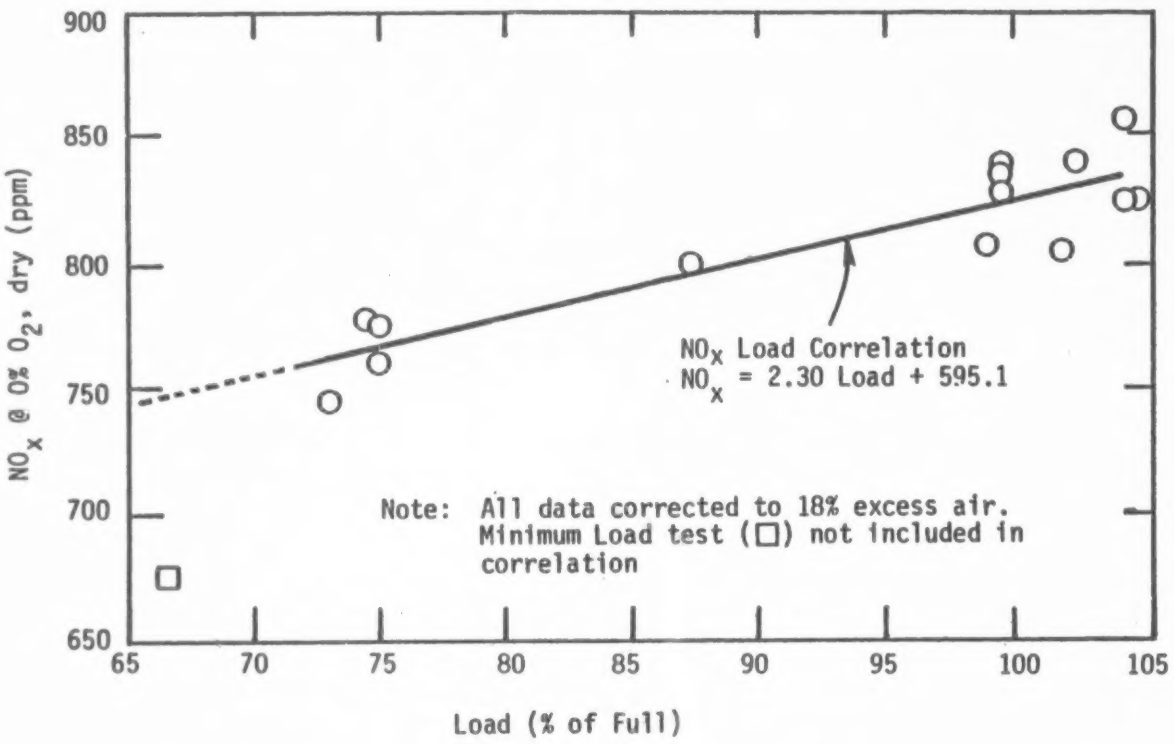


Figure 2-11. Effect of load on NO_x.

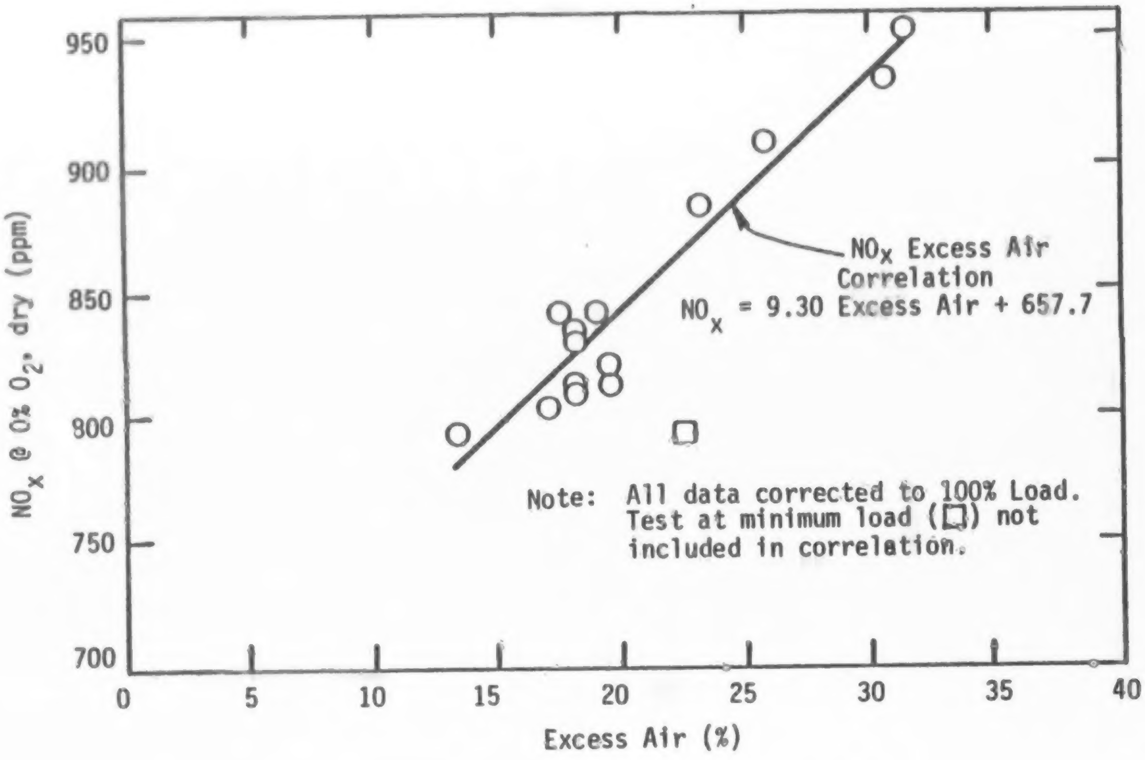
ppm low. It should be noted that this point was obtained while firing exceptionally wet coal and this may have affected NO_x emissions.

Figure 2-12 is a cross-plot showing the effect of excess air at constant firing rate. All data points were corrected to 100 percent load using the correlation. Again, all data points lie within a ±25 ppm band of the correlation except for the low load point.

CO emissions were insensitive to load and excess air over the range evaluated. Figure 2-13 shows the effect of load on CO emissions for the subset of the data within the range 17 to 20.5 percent excess air. There appears to be no systematic effect of excess air. The data scatter is about ±10 ppm from the average of 40 ppm. The effects of excess air are shown in Figure 2-14. Although the averages for the three load ranges vary somewhat, the differences are within the range of data scatter.

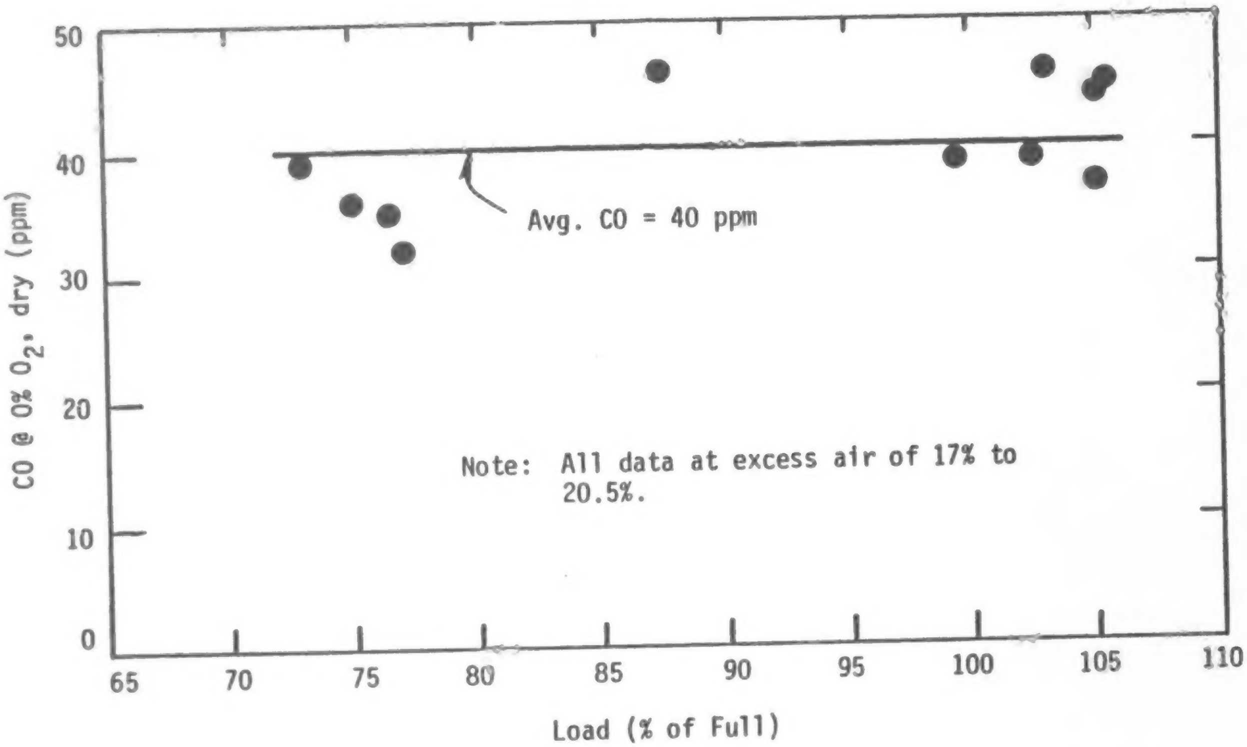
The effect of core air valve position was evaluated at 65 and 100 percent load and nominal excess air. Closing the core air valve from the normal full open position caused the flame to retract into the burner throat. The effects on NO_x emissions are shown in Figure 2-15. All data points have been corrected to 18 percent excess air. At full load, closing the core air valve increased NO_x emissions. At low-load the effect is unclear. In comparison with the NO_x correlation which applies to the full open core air valve position, closing the core air valve decreases NO_x emissions, the opposite of the effect at full load. However, in comparison to the data point at 67 percent load with the core air valve full open, closing the core air valve increases NO_x emissions. Note that the data point at 67 percent load with the core air valve open was not included in the correlation.

The effects of register position were evaluated at the same loads as the core air valve. However, only small changes in register position were made due to the pronounced effects on flame characteristics. Closing the registers drew the flame back into the throat in the same manner as closing the core air valve. Opening the registers increased the flame stand-off distance, resulting in a loss-of-flame indication. The effect on NO_x



Note: All data corrected to 100% Load. Test at minimum load (□) not included in correlation.

Figure 2-12. Effect of excess air on NO_x.



Note: All data at excess air of 17% to 20.5%.

Figure 2-13. Effect of load on CO.

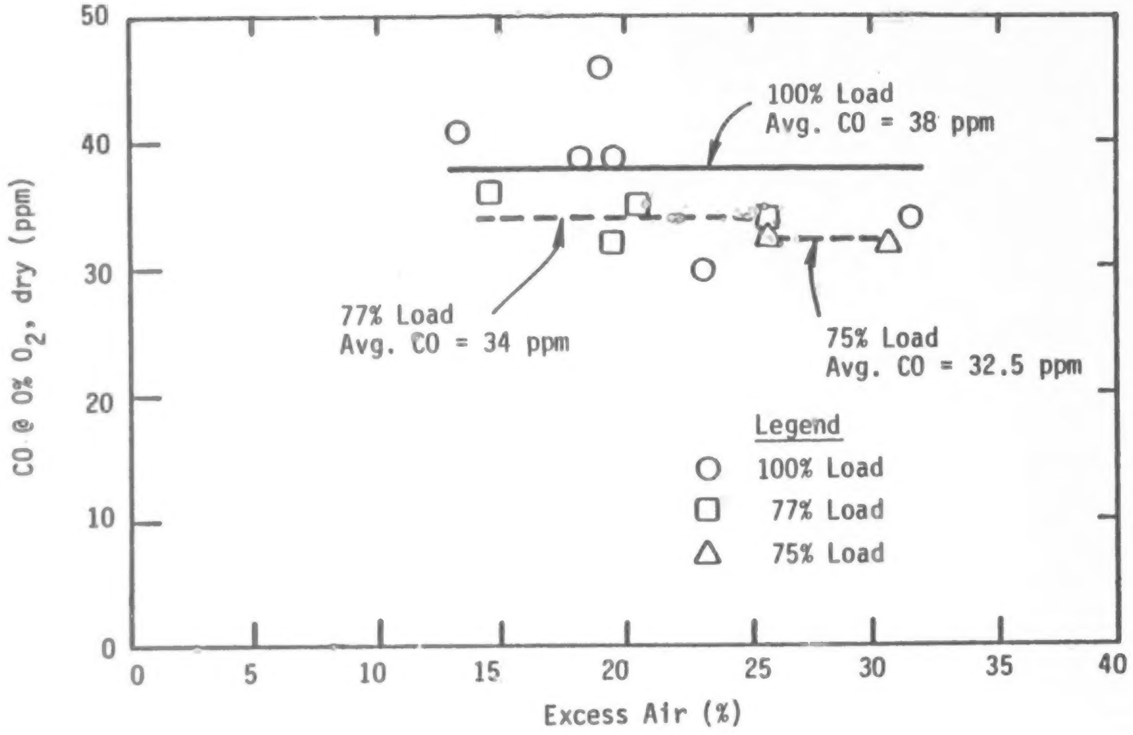


Figure 2-14. Effect of excess air on CO.

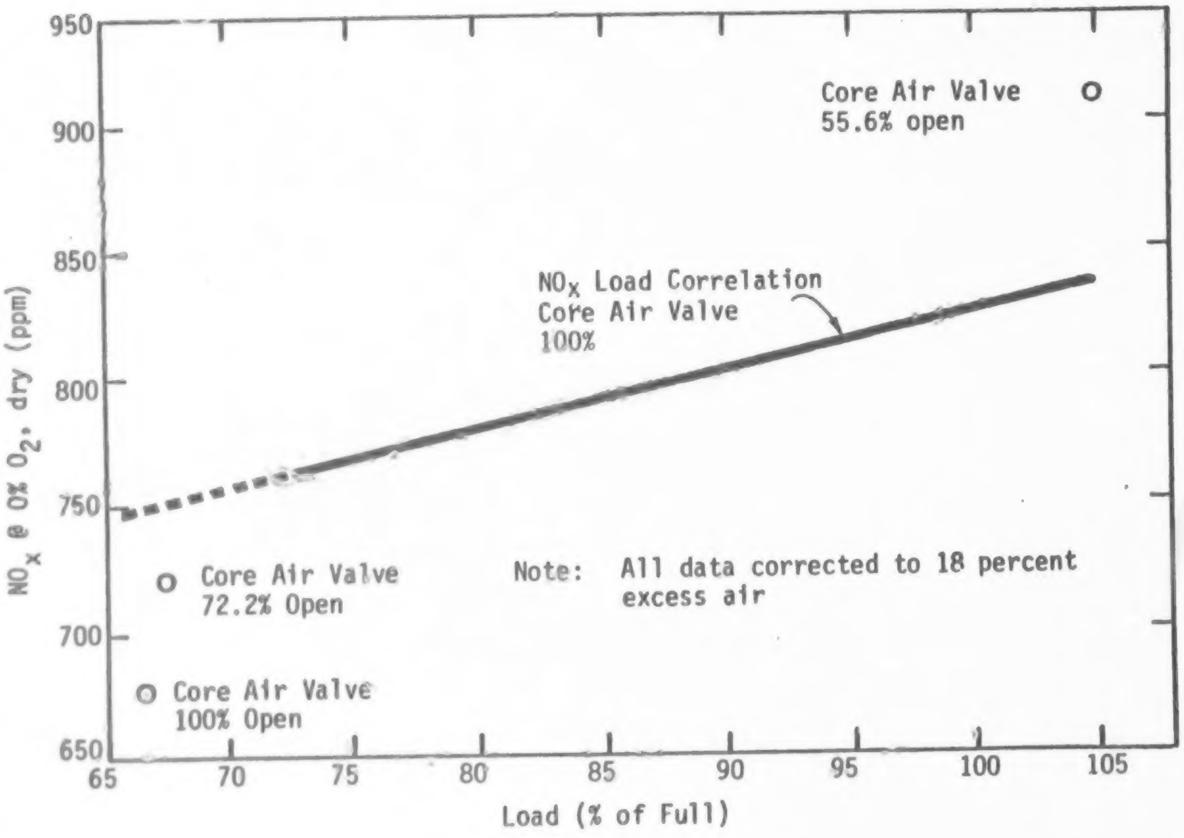


Figure 2-15. Effect of core air valve setting on NO_x.

emissions is shown in Figure 2-16. At full load the nominal operating condition produced the lowest NO_x emissions. Opening or closing the registers from the baseline settings increased NO_x emissions. The interpretation of the effect of register position at low load is subject to the same problem as the core air valve effect: the NO_x emissions for the nominal setting are considerably lower than the correlation.

The effects of core air valve and register variations on CO emissions are shown in Figure 2-17. CO emissions appear to be independent of the burner settings at high and low load.

Particulate concentrations were measured over a range of load, excess air as well as mill bias. The measurement location was upstream of the air heater and thus not affected by the cyclone or scrubber particulate removal. However, no relationship between particulate emissions and operating conditions was apparent. Figure 2-18 shows a plot of particulate emissions for the three test series versus excess air. Particulate emissions are expressed as the ratio of particulate mass to mass of ash in the coal to compensate for varying ash concentrations in the coal. Although the particulate concentration was higher during the mill bias test, carbon utilization in this test was comparable to other test conditions. Thus, the higher particulate is probably due to measurement rather than an increase in particulate. The particulate emissions were primarily affected by variations in the ash content of the coal. Figure 2-19 shows the similarity of particulate concentration changes to coal ash content changes. Carbon utilization was calculated from carbon and ash analyses of coal and particulate samples for each particulate test. The carbon utilization varied from 99.12 to 99.67 percent during the three test series, thus showing high combustion efficiency for each test.

Particle size distribution was measured at full and reduced load during the optimization tests. No change in size distribution was noted due to the change in load. Figure 2-20 compares the size distribution measurements at full load and 70 percent of full load.

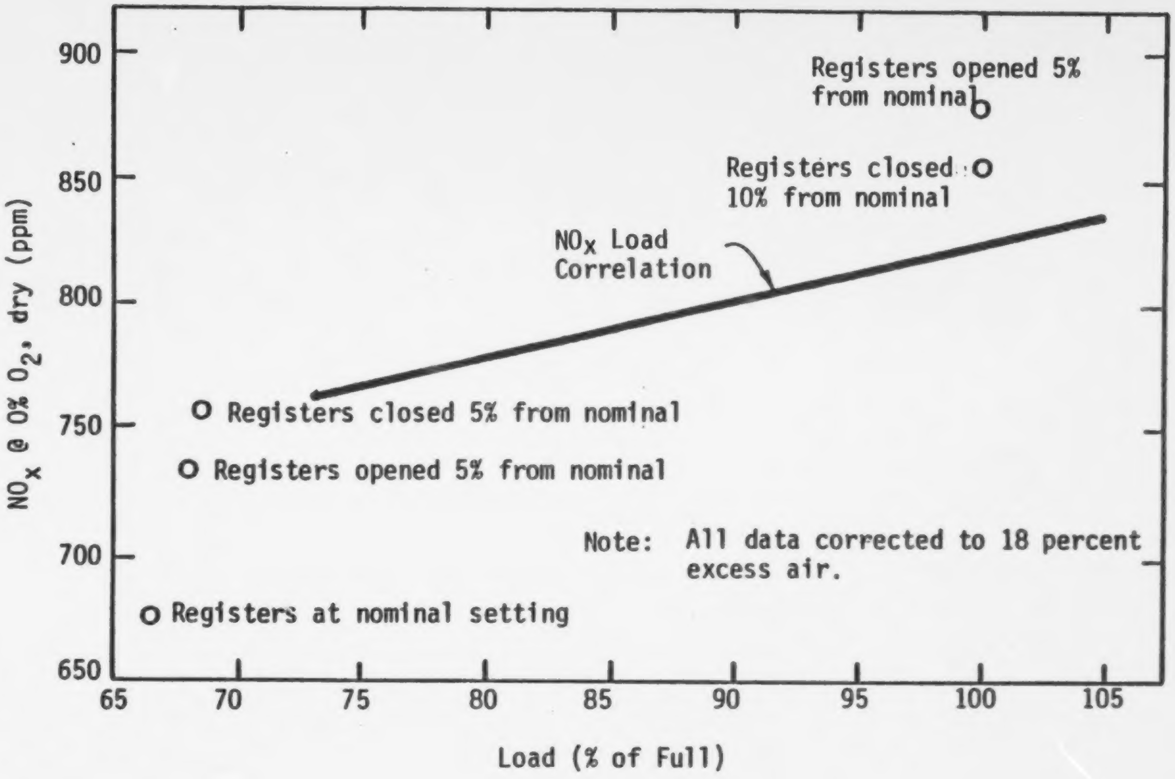


Figure 2-16. Effect of register position on NO$_x$.

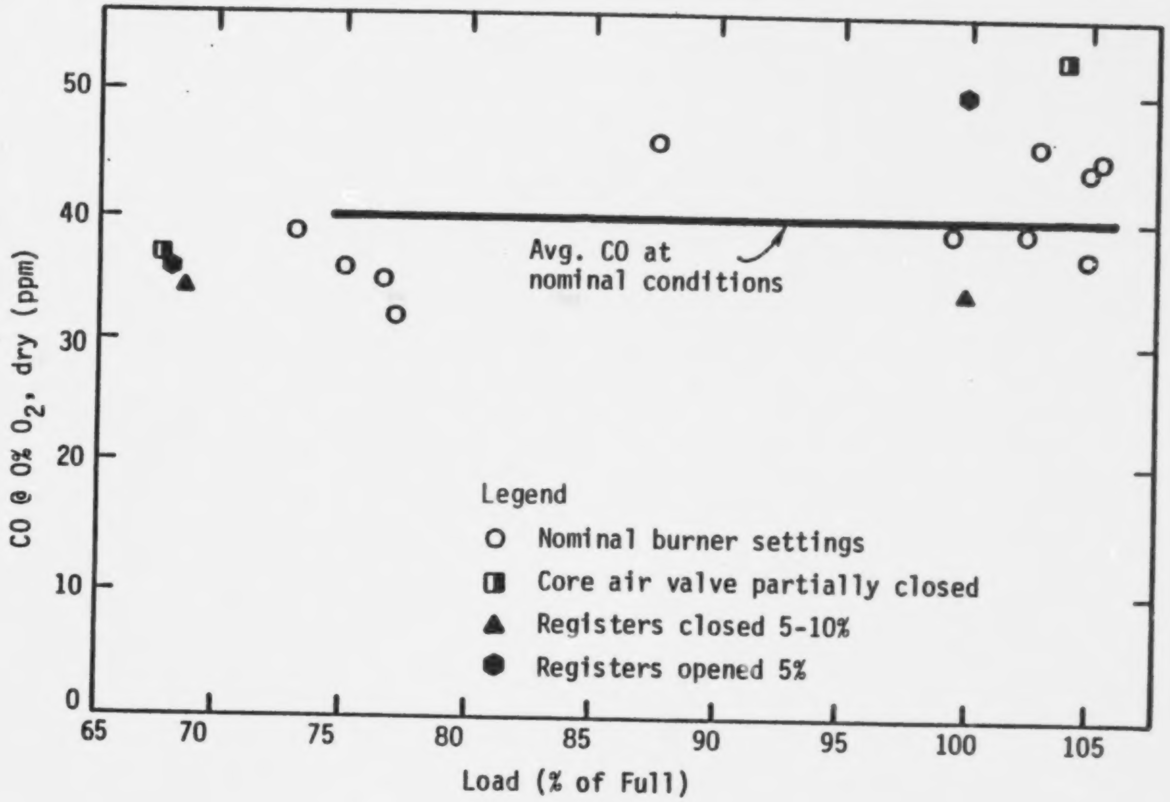


Figure 2-17. Effect of register and core air valve settings on CO.

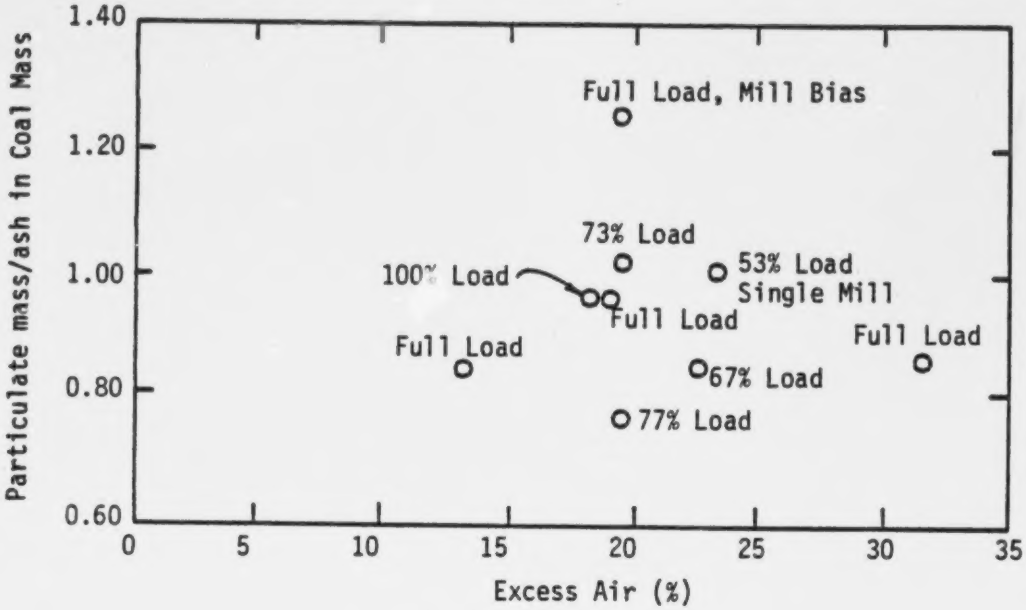
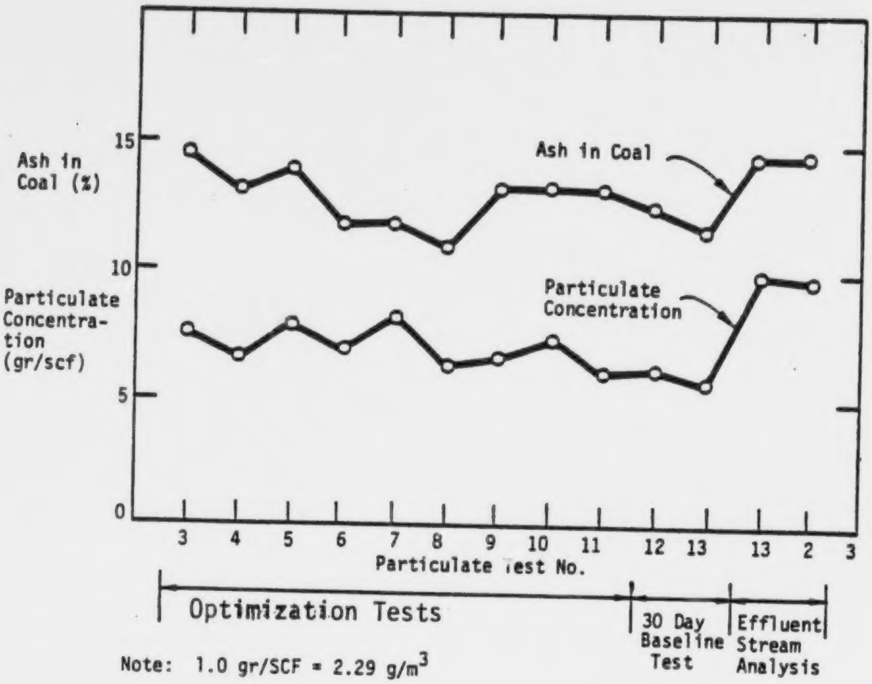


Figure 2-18. Particulate test results.



Note: 1.0 gr/SCF = 2.29 g/m^3

Figure 2-19. Relationship of ash in coal to particulate concentration.

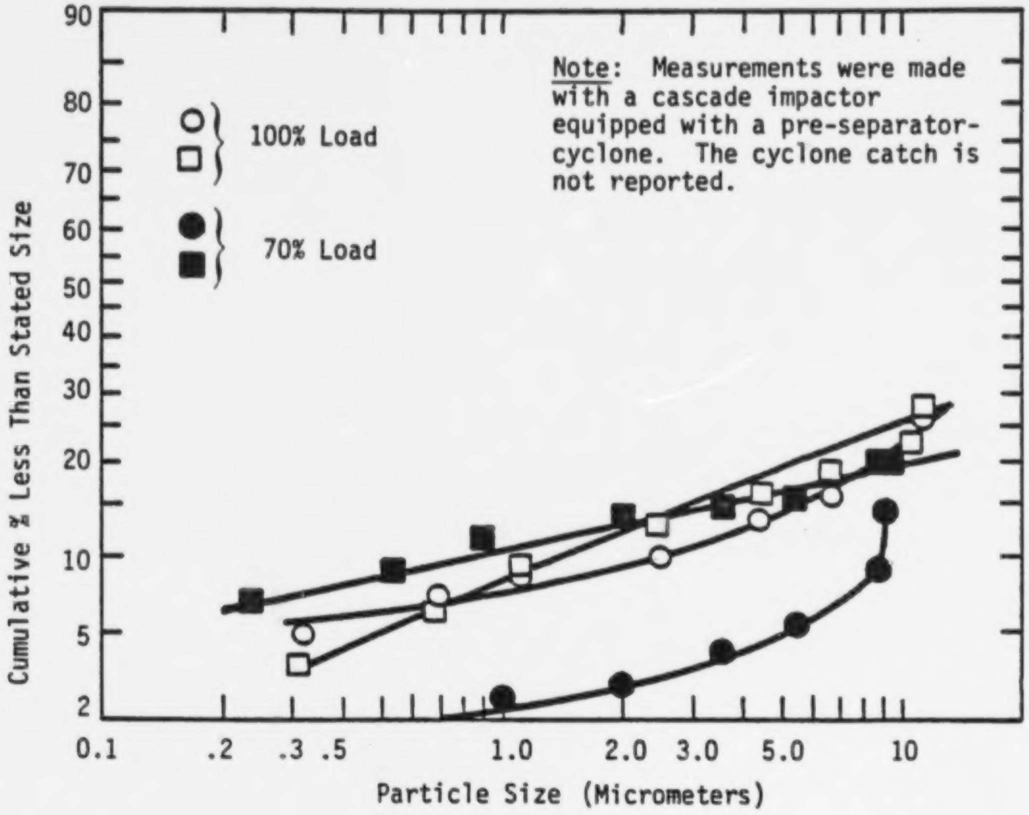


Figure 2-20. Comparison of fly ash particle size distribution at 100 percent and 70 percent of full load.

2.3.4 Low NO_x Operation

The objective of this program was to demonstrate the reductions in NO_x emissions which can be achieved by retrofitting the distributed mixing burners. The reductions in NO_x emissions are measured from the minimum NO_x emissions which can be achieved without burner replacement or other major modifications. During this test series, low excess air and bias firing were evaluated as possible combustion modifications to reduce NO_x emissions.

As previously discussed, the minimum excess O_2 level tested was 2.5 percent, corresponding to an excess air level of 13.5 percent. At this condition, combustion was satisfactory and the NO_x emissions were reduced to 796 ppm, a 4 percent reduction from the baseline (826 ppm). This is an insignificant reduction.

Bias firing involves operating the upper and lower burners at different firing rates and/or excess air levels. This was achieved by varying the coal feed rates to the two pulverizers which supply the upper and lower burners separately. The coal feed rate to the lower burners was increased while the coal feed rate to the upper burners was decreased maintaining the total coal feed rate constant. The net effect was firing a majority of the coal through the lower burners at low excess air while providing additional air through the upper burners to complete combustion. This partial staging reduced NO_x emissions as shown in Figure 2-21. The maximum bias was limited by the minimum feeder speed on the mill supplying the upper burners. The stoichiometry at the lower burners decreased as the bias increased to 95 percent theoretical air (substoichiometric) at the maximum bias. The effects of biasing the registers was evaluated also. The registers of the bottom burners were closed five percent from the nominal settings. However, NO_x emissions increased as shown in Figure 2-21.

As the mill bias was increased, the ignition point of the lower flames was observed to move slightly out of the exit (2 to 3 inches) and the path of unburned coal and air passing through the exit appeared darker than normal. The flame volume also increased and the flames were observed to roll along

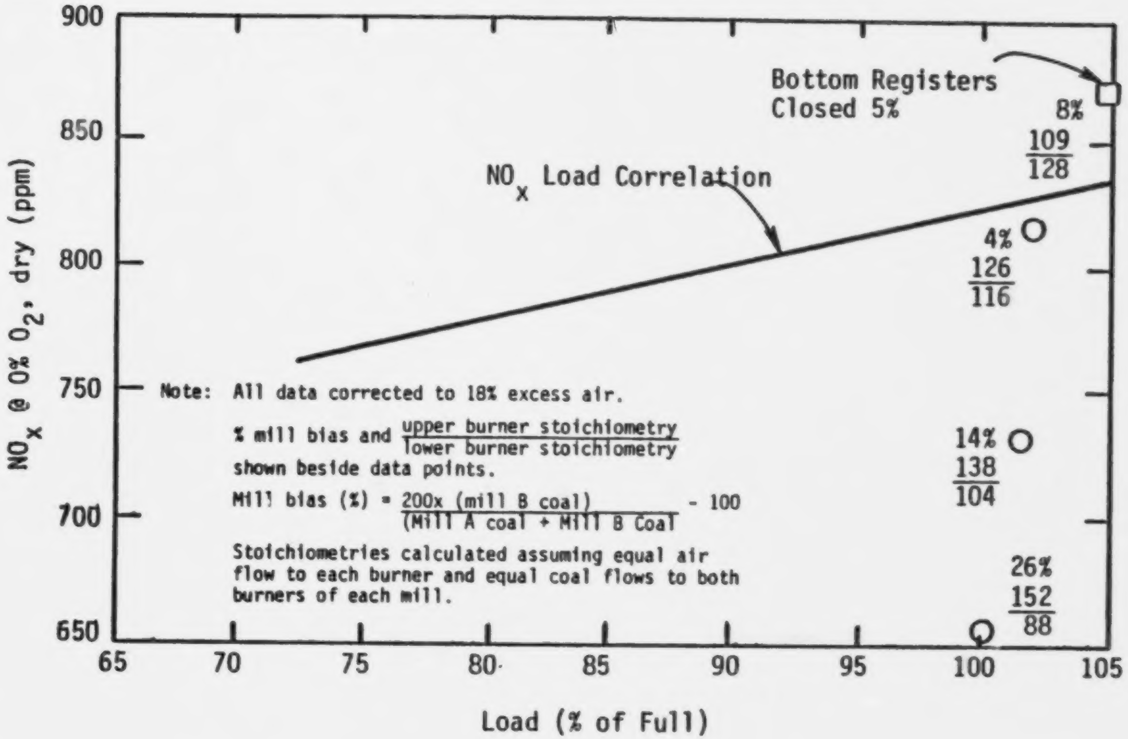


Figure 2-21. Effect of bias firing on NO_x.

both sidewalls. The concentrations of O_2 and CO measured at the sidewalls showed almost no O_2 and very high CO levels. However, the CO in the exhaust remained low even at the maximum bias shown in Figure 2-21.

The maximum bias resulted in a 19 percent reduction from the baseline (826 ppm). This is a significant reduction, but sustained operation at this condition is not desirable. Ash fusion temperatures are lower under reducing conditions and this could cause furnace slagging and related corrosion. It was not possible to evaluate these long term effects in these brief tests.

3.0 PROTOTYPE DMBs

At the inception of this program, data were available from tests of several research DMBs in the SWS and LWS test facilities. These burners were generic designs which produced the desired fuel/air mixing but were not constructed using commercial burner components or manufacturing processes and did not meet commercial burner standards. The objectives of the prototype DMB work were to: (1) define DMB design criteria based on the test of the research DMBs, (2) integrate these criteria with commercial burner components and produce a burner meeting the requirements of the host boiler and (3) verify/optimize its performance through tests in the LWS. Since the LWS is a combustion test facility, not a field operating industrial or utility boiler, some assurance was required that performance measured in the LWS would be representative of burner performance achievable in the host boiler. To provide this assurance, an Intervane Burner similar to those originally installed in the host boiler was tested in the LWS also. Similarity between the performance of the Intervane Burner in the LWS and host boiler was used as an indication that the DMB performance would be similar also.

Several prototype DMBs were tested. Here the term "prototype" refers to burner designs which are full scale, functionally identical to the burners to be installed in the host boiler and are constructed with commercial burner components and manufacturing methods but are not intended for long term field operation. For example, the prototype burners were constructed of low cost carbon steel while burners designed for long term commercial service may have stainless steel or other heat resistant materials in key areas. The prototype burners were designed to be "flexible" so that key parameters could be adjusted to optimize performance. The intent was to use the optimized parameters for the field operable burners.

Table 3-1 summarizes the prototype burner tests. Three burner designs were tested:

1. Initial prototype burner
2. Foster Wheeler prototype burner

TABLE 3-1. PROTOTYPE DMB TEST SUMMARY

DATE	PROTOTYPE BURNER DESIGN	FURNACE	COAL	SORBENT INJECTION	COMMENTS
12/79	INITIAL	OLD LWS	UTAH	NO	BRIEF TESTS OLD LWS FAILED
12/80	INITIAL	NEW LWS	UTAH INDIANA	NO	FLAME INSTABILITY AT DESIGN POINT - OTHERWISE ACCEPTABLE
2/81	FOSTER WHEELER	NEW LWS	INDIANA UTAH ILLINOIS	YES	FLAME STABLE AT DESIGN POINT COMMERCIAL STANDARDS MET
6/81	FOSTER WHEELER	MT	UTAH INDIANA	YES	EVALUATION OF FURNACE CONFINEMENT EFFECTS
11/83	FINAL	NEW LWS	UTAH INDIANA	YES	FLAME STABLE AT DESIGN POINT BEST OVERALL PERFORMANCE

3. Final prototype burner

The "initial" prototype burner was designed by integrating the DMB design criteria developed from analysis of the research DMB test results with Foster Wheeler burner components. The "Foster Wheeler" prototype burner was the same as the initial prototype burner except that the coal nozzle and burner exit geometry were modified to match the Foster Wheeler Controlled Flow Burner. The specific geometry and design parameters for this exit geometry are proprietary to Foster Wheeler. The field operable burners installed in the WIPCO unit are identical to this design with upgraded materials of construction. The "final" prototype burner design was a modification to the initial prototype burner design which attempted to optimize performance for minimum NO_x emissions commensurate with maximum flame stability and combustion efficiency.

The prototype burners were tested in three test facilities:

1. Old Large Watertube Simulator (Old LWS)
2. New Large Watertube Simulator (New LWS)
3. Medium Tunnel (MT)

The design parameters for these facilities are listed in Table 3-2 and the facility designs are discussed in Appendix A. Briefly, the LWS facilities were similar in design to small front wall fired industrial and utility boilers. The old LWS had no refractory in the furnace walls and had a relatively cool thermal environment. The geometry of the new LWS was modified slightly and is almost identical to the WIPCO furnace. Refractory insulation was added to the vertical furnace walls to provide a hotter thermal environment similar to that of the WIPCO furnace. The MT is a large horizontal "tunnel furnace" with a thermal environment similar to the LWS (in terms of heat release per cooled surface areas) but with a much smaller furnace volume.

The initial prototype burner was tested in the old and new LWS. This provided an opportunity to evaluate performance in two furnace thermal

TABLE 3-2. COMBUSTION TEST FACILITY CHARACTERISTICS

Furnace	Old LWS	New LWS	MT
Shape	Rectangular with hopper and nose	Rectangular with hopper and nose	Horizontal cylinder
Firing Configuration	Front wall	Front wall	End
Exhaust	Top	Top	End
Firing Capacity (Btu/hr)	125×10^6	150×10^6	80×10^6
Width (ft)	16	16	14 (dia)
Firing Depth (ft)	18	22	20
Overall Height (ft)	54	50	--
Cooling	External water spray	External water spray	External water spray
Refractory Insulation in Burner Zone	None	Side walls (from knuckle up to 16 ft)	50% of circumference and 100% of target wall
Heat Release/Cooled Surface* (Btu/hr-ft^2) at:	45,000	87,000	90,000
Burner Firing Rate (10^6 Btu/hr)	70	70	50

*BZLR for LWS

environments under conditions where the furnace geometries are essentially the same. The Foster Wheeler prototype burner was tested in the new LWS and MT. This provided an opportunity to evaluate performance in two furnace confinements which have essentially the same thermal environment. The final prototype burner was tested in the LWS only.

As indicated in Table 3-1, a range of coals was fired. All were high volatile bituminous coals. The Utah coal is a low sulfur fuel that was used as the baseline fuel for the development DMB tests. The Indiana coal is from the Three States Trucking mine and is the coal which was fired for a considerable time period in the WIPCO unit. The composition of this coal varies substantially. The Illinois coal is a high sulfur bituminous coal. Analysis of these coals are presented in Appendix B of Volume 2.

The tests of each prototype burner focused on NO_x emissions. In addition, the tests of the Foster Wheeler and final prototype burners were conducted with limestone injection for SO_2 control. Several reports have been published detailing the prototype burner development and test results. The development of the DMB design criteria, the design of the initial prototype burner and the Intervane Burner test results are discussed in Distributed Mixing Burner (DMB) Engineering Design For Application To Industrial and Utility Boilers (Folsom, et al, 1984). The First Annual Report summarizes this information. The tests of the initial and Foster Wheeler prototype burners are discussed in the Second and Third Annual Reports, respectively.

The remainder of this section summarizes the results presented in these previous reports and presents the results of the final prototype burner tests. The following subsections discusses the Intervane Burner test results in the old LWS. Subsections 3.2 and 3.3 discuss the development of the DMB design criteria and the initial prototype burner design as well as tests in the old and new LWS. The Foster Wheeler and final prototype burner designs and test results are presented in subsections 3.4 and 3.5, respectively. Finally, subsection 3.6 discusses sorbent injection test results using the Foster Wheeler and final prototype burners. Finally, subsection 3.7 presents the results of an isothermal flow study of tertiary air mixing in the furnace.

3.1 Intervane Burner Tests

The objective of this test was to "calibrate" the LWS test facility by comparing the performance of the commercial burner originally installed in the host boiler in two furnaces: the LWS and the host boiler furnace. The baseline boiler test was discussed in the previous subsection. This subsection presents the results of the LWS test.

3.1.1 Burner Design

The Intervane Burner is Foster Wheeler's standard commercial pre-NSPS burner. It has been installed on a large number of front-wall and oppose-wall fired industrial and utility boilers with individual burner firing rates up to 300 x 10^6 Btu/hr. The Intervane Burner is designed to produce rapid fuel/air mixing and a stable flame over a wide range of operating conditions. The flame is short and intense and thus compatible with small and large furnace depths. Prior to the promulgation of the EPA NSPS, the Intervane Burner was Foster Wheeler's standard pulverized coal burner. The WIPCO host unit is a pre-NSPS unit and was equipped with Intervane Burners. Following the promulgation of the NSPS, Foster Wheeler used over-fire air ports or air ports located between the upper burner rows in conjunction with the Intervane Burner. Subsequently, Foster Wheeler developed the Controlled Flow and the Controlled Flow-Split Flame low NO_x burners. These burners are now offered as Foster Wheeler's standard pulverized coal-fired burners.

The Intervane Burner test in the LWS was conducted in the fall of 1979 prior to the selection of the host boiler. Foster Wheeler provided an Intervane Burner representative of those installed at the host boilers under consideration. The burner tested had a firing capacity of 90 x 10^6 But/hr and is illustrated schematically in Figure 3-1. The coal nozzle is a tapered annulus with a tangential inlet which imparts swirl to the primary coal/air mixture. The pulverized coal particles are thrown by centrifugal force to

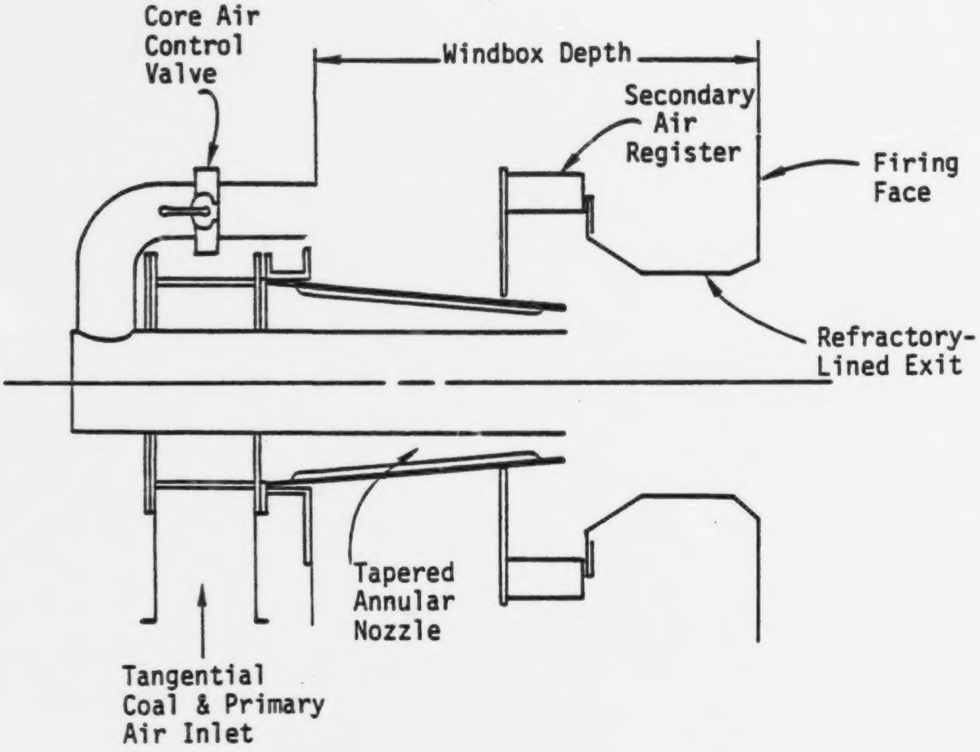

Core Air
Control
Valve
Windbox Depth
Secondary
Air
Register
Firing
Face
Refractory-
Lined Exit
Tapered
Annular
Nozzle
Tangential
Coal & Primary
Air Inlet

Figure 3-1. Foster Wheeler intervane burner.

the outer barrel. This provides for a uniform distribution of coal around the circumference. Secondary combustion air is supplied from a windbox through a single adjustable register. Normally, the register is positioned at approximately 25 to 50 percent open and in this range it produces considerable secondary air swirl. The center portion of the burner is supplied with windbox air which is controlled by a butterfly valve. Foster Wheeler terms this air flow as "tertiary air". However, to avoid confusion with the DMB outboard tertiary air ports, it will be called "core air" in this report. Normally, the core air is a small fraction of the total combustion air. It cools the inner barrel of the nozzle and prevents pulverized coal particles from moving into the barrel where coking could occur. An oil-fired igniter is normally provided either along the axis of the burner through the core air passage or through a register vane passage. Scanners for both the igniter and main flame are provided also. The burner exit is long and refractory lined. In field installation, it is formed by bending water wall tubes to form a circular opening in the furnace wall, studding the tubes and covering them with refractory. The exit geometry provides for considerable pre-mixing of the fuel and air in the exit. This produces an intense flame and high NO_x emissions.

Table 3-3 lists the Intervane Burner dimensions, full load operating conditions and velocities. Since the secondary air enters the throat non-axially, the secondary area and velocity are not clearly defined. The values listed are based on axial flow in the equivalent annulus between the nozzle exit and the throat, as well as the characteristics of the Utah coal used in the LWS tests.

3.1.2 Test Results

The Intervane Burner was installed in the old-LWS in a front wall fired configuration. To ensure that the burner was operated in a manner similar to full scale field operating boilers, the operating point was established by a Foster Wheeler service engineer. A majority of the tests were conducted at the following baseline operating conditions and settings:

TABLE 3-3. INTERVANE BURNER CHARACTERISTICS

Dimensions	
Core Diameter	12.0
Core Area (in.^{2})	113.0
Nozzle Diameter (in.)	18.5
Primary Radial Thickness (in.)	1875
Primary Area (in.^{2})	141.1
Throat Diameter (in.)	28.0
Secondary Radial Thickness (in.)	4.75
Secondary Area (in.^{2})	346.9
Throat Area (in.^{2})	615.7
Nozzle Setback from Firing Face (in.)	24.0
Operating Conditions	
Firing Capacity (10^6 Btu/hr)	90.0
Air Requirement (lb air/10^6 Btu)	7.57*
Primary Stoichiometry (% T.A.)	18
Primary Temperature (°F)	150
Overall Stoichiometry (% T.A.)	120
Windbox Temperature (°F)	600
Velocities	
Primary (ft/sec)	52.2
Secondary (ft/sec)	213.7
Throat (ft/sec)	132.6

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*Based on Utah coal

Firing rate	80×10^{6} Btu/hr
Primary Stoichiometry	18% theoretical air
Primary Temperature	160°F
Secondary Temperature	600°F
Register Position	40° open
Core Air Position	78° open

In general, the burner performance was similar to that observed in the field. The flame was short, bright, intense and stable. The flame shape is sketched in Figure 3-2. The base of the flame was within the cylindrical portion of the exit and filled the divergent portion. In the furnace, the flame expanded rapidly and was about 12 ft (5 throat diameters) long. The burner controls including the register and core air control valve affected the flame shape and optimum results were obtained with the register set at 40° open and the core air valve at 78° open. Throughout the tests, stack opacity was low except for low excess air conditions where some black smoke was observed. The smoke was generally a light gray haze.

Figure 3-3 shows the NO_x and CO emissions for these tests conditions as functions of overall stoichiometry for the baseline condition and alternate register positions. There is no discernible affect of register position on emissions over the range tested. However, it should be noted that for both positions the base of the flame was within the burner exit. The relationship between emissions and overall stoichiometry was as expected: NO_x emissions increased and CO emissions decreased as excess air increased. At the design point excess air (18 percent) NO_x emissions were 410 ppm and CO emissions were 190 ppm (corrected to 0 percent O_2, dry).

Figure 3-4 shows the effect of load variations. The primary air flowrate was maintained constant as load varied which is the normal operating procedure at the WIPCO unit. Thus, the primary stoichiometry increased as load decreased. As expected, NO_x emissions decreased with load and the "knee" of the CO curve occurred at a higher overall stoichiometry as load decreased. Additional tests were conducted with independent variation of load and primary stoichiometry to uncouple their affects. Figure 3-5 shows

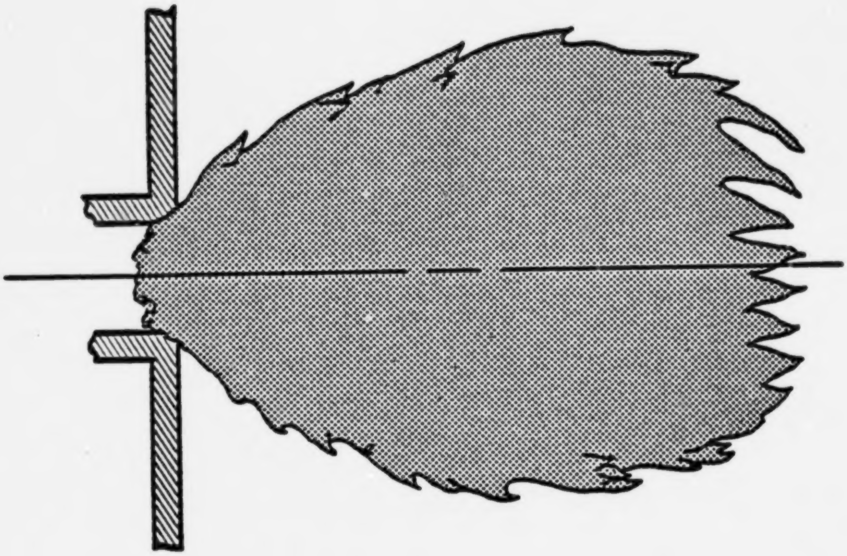


Figure 3-2. Intervane burner flame shape in LWS test facility.

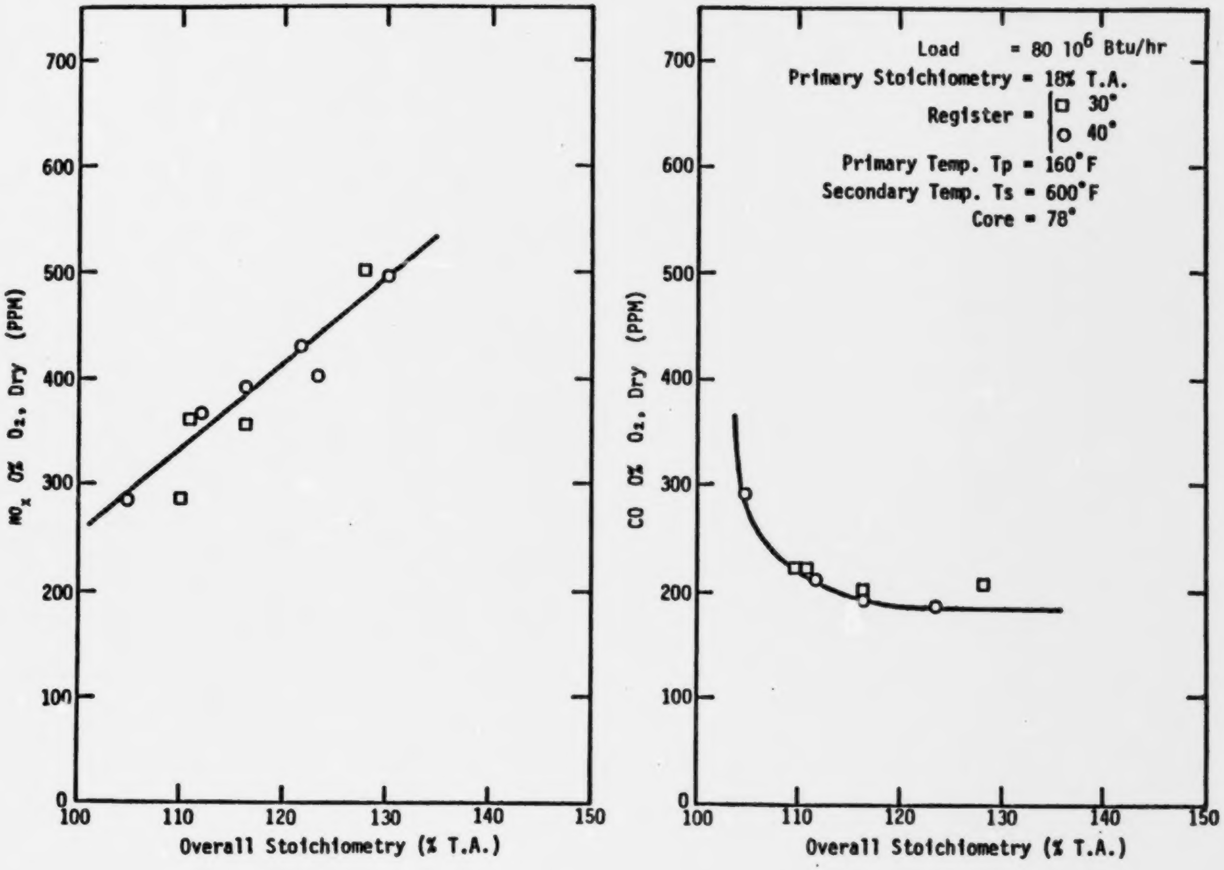


Figure 3-3. Intervane burner data: Effect of register setting at constant load.

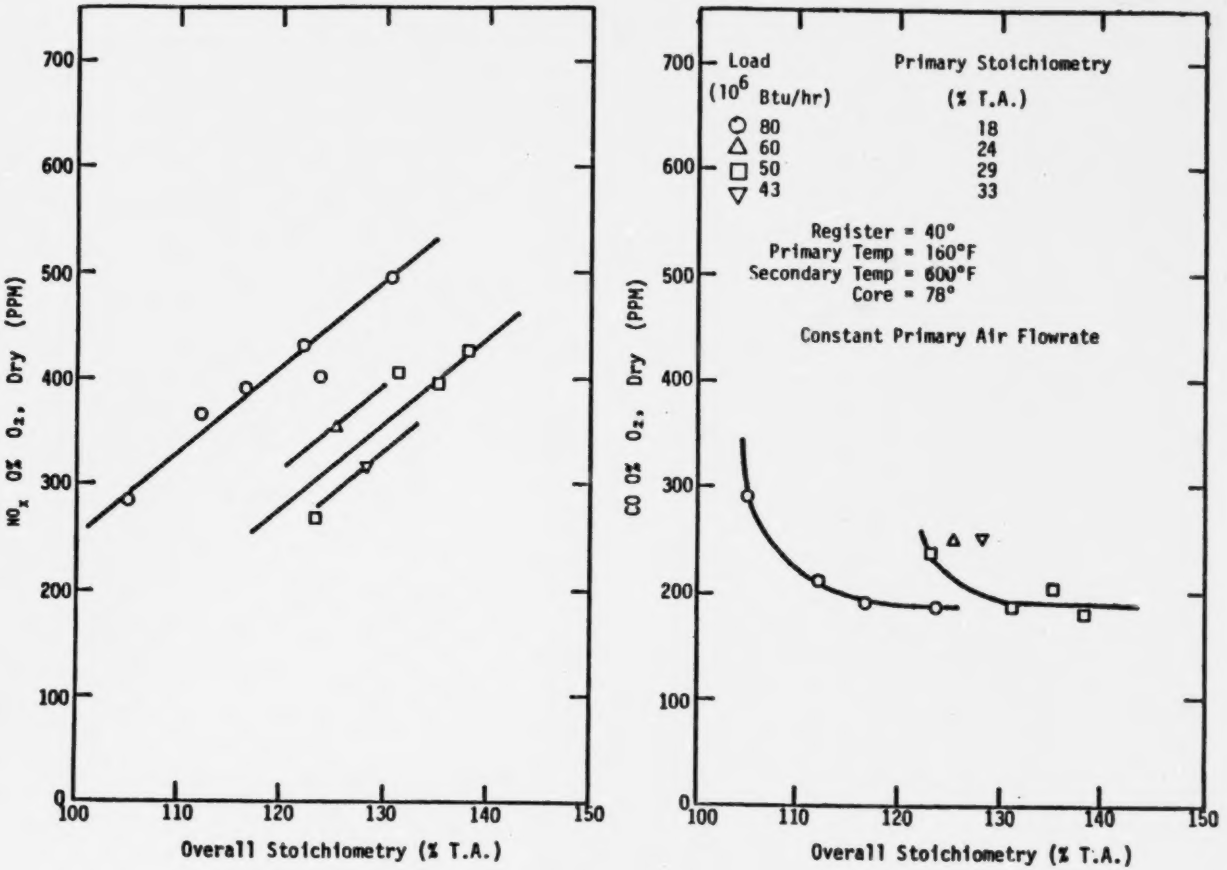


Figure 3-4. Intervane burner data: effect of overall stoichiometry at various loads.

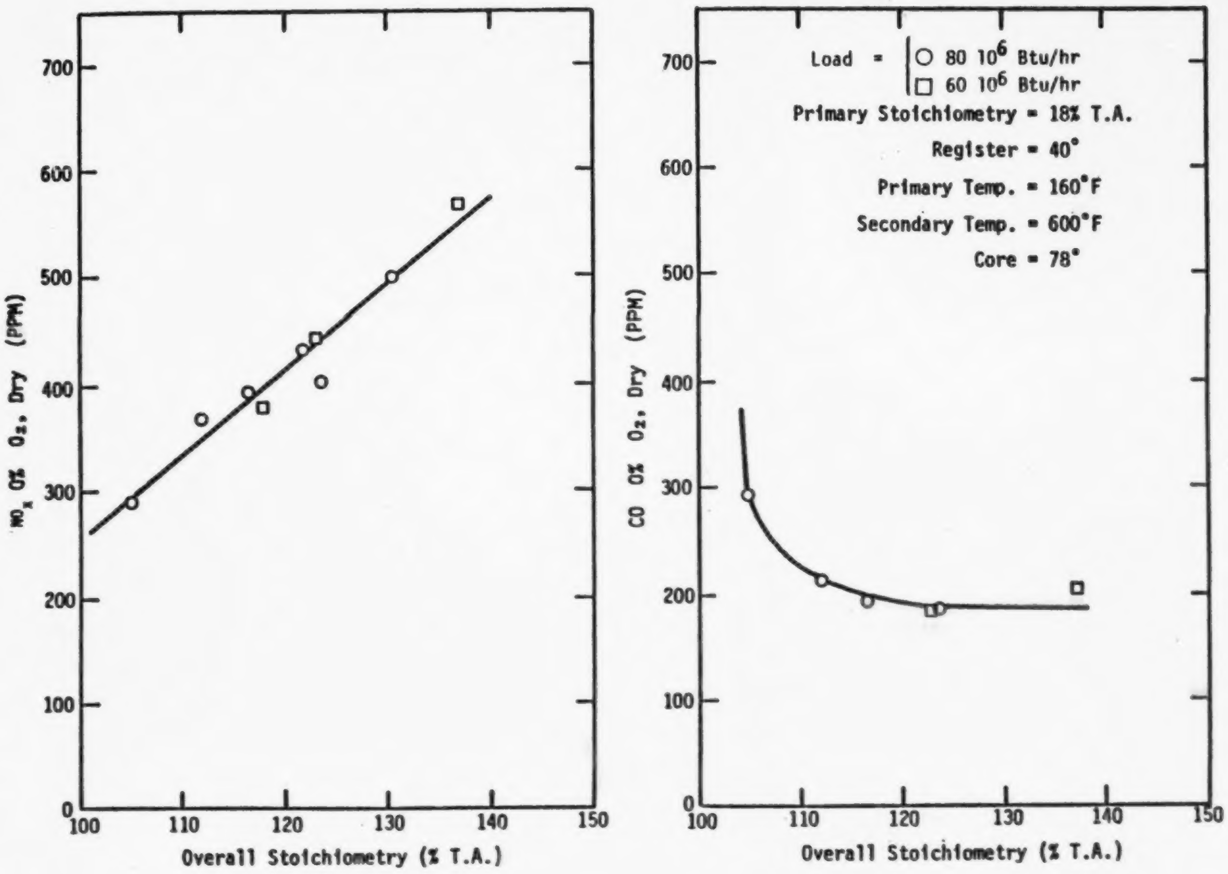


Figure 3-5. Intervane burner data: effect of load at constant primary stoichiometry.

results for loads of 60 and 80 x 10^6 Btu/hr at 18 percent theoretical air in the primary. There appears to be no effect of load on emissions under these conditions. Figure 3-6 shows results for a load of 60 x 10^6 Btu/hr and primary stoichiometries of 18 and 24 percent theoretical air. The higher primary air level resulted in lower NO_x emissions and higher CO emissions. Figure 3-7 compares the two methods of varied load: constant primary air flow rate and constant primary stoichiometry. The "data points" in Figure 3-7 were interpreted from the trends of the data in Figures 3-3 to 3-6 evaluated at a fixed 125 percent theoretical air. These results show that the pulverizer operating condition (primary stoichiometry and flowrate) had a significant impact on NO_x emissions.

3.1.3 Comparison: LWS & Field Performance

The qualitative performance of the Intervane Burner in the LWS and WIPCO unit were similar. In both tests the flames were short, bright, intense and stable. In the LWS test, the flame was adjusted by the Foster Wheeler service engineer with the base within the burner exit. However, the base of the flame could be moved out into the furnace by changing the burner adjustments (register and core air valve). During the WIPCO baseline tests, the operators adjusted the burners to maintain some distance between the base flame and the furnace wall. In the field test, the flames were stable and CO emissions were uniformly low across the full range of excess air. However, the lowest excess O_2 tested was 2.5 percent which corresponds to about 113 percent theoretical air. The LWS test results are similar across this stoichiometry range but CO emissions increased sharply at lower excess air.

The quantitative performance including NO_x and CO emissions in the LWS and field tests were different. In the field test, CO emissions were less than 50 ppm under all conditions tested. In the LWS under comparable conditions, CO emissions were about 200 ppm, a factor of four higher. This difference is contributed to the thermal environment of the old LWS which is considerably colder than the WIPCO unit. A cold thermal environment results in quenching of CO oxidation reactions in the upper furnace leading to high CO emissions. The effect of thermal environment on CO emissions was

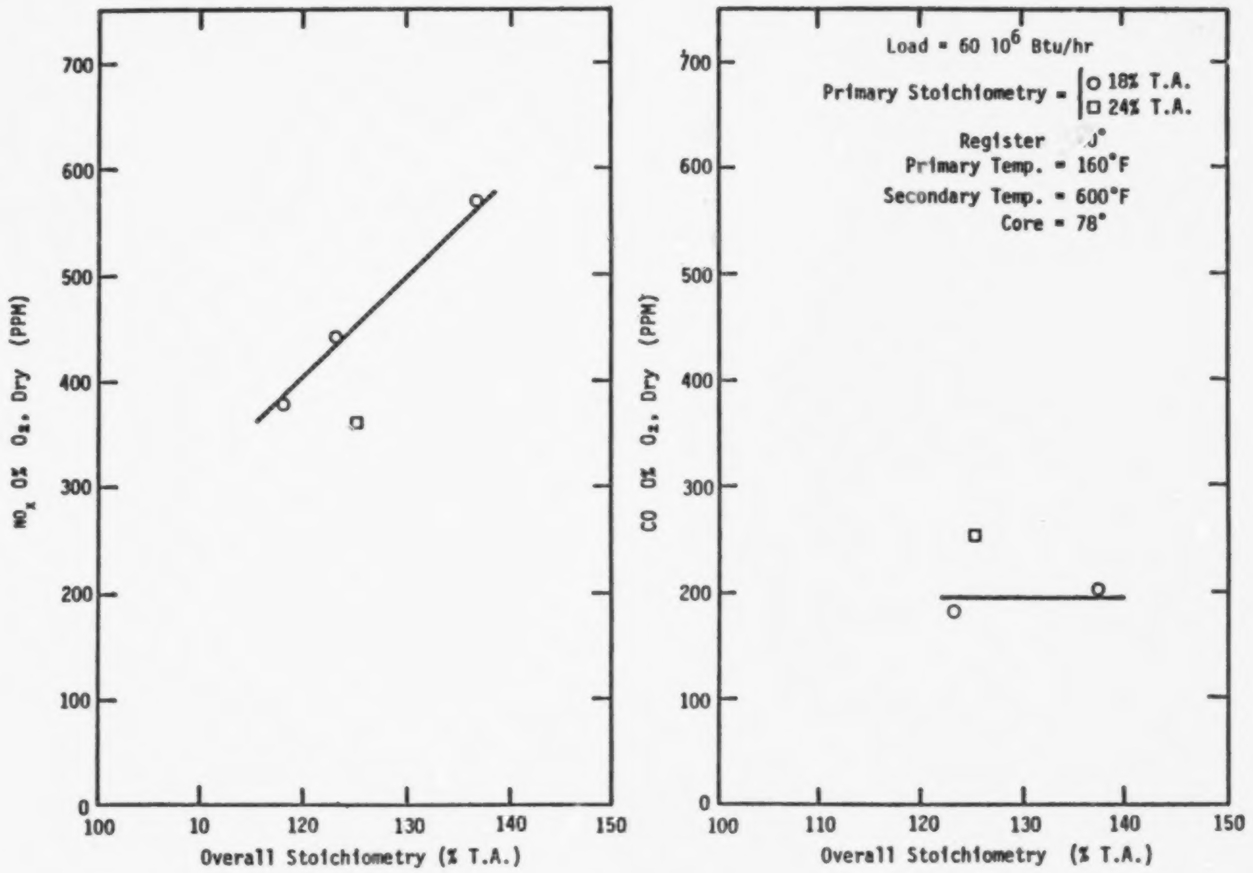


Figure 3-6. Intervane burner data: effect of primary stoichiometry.

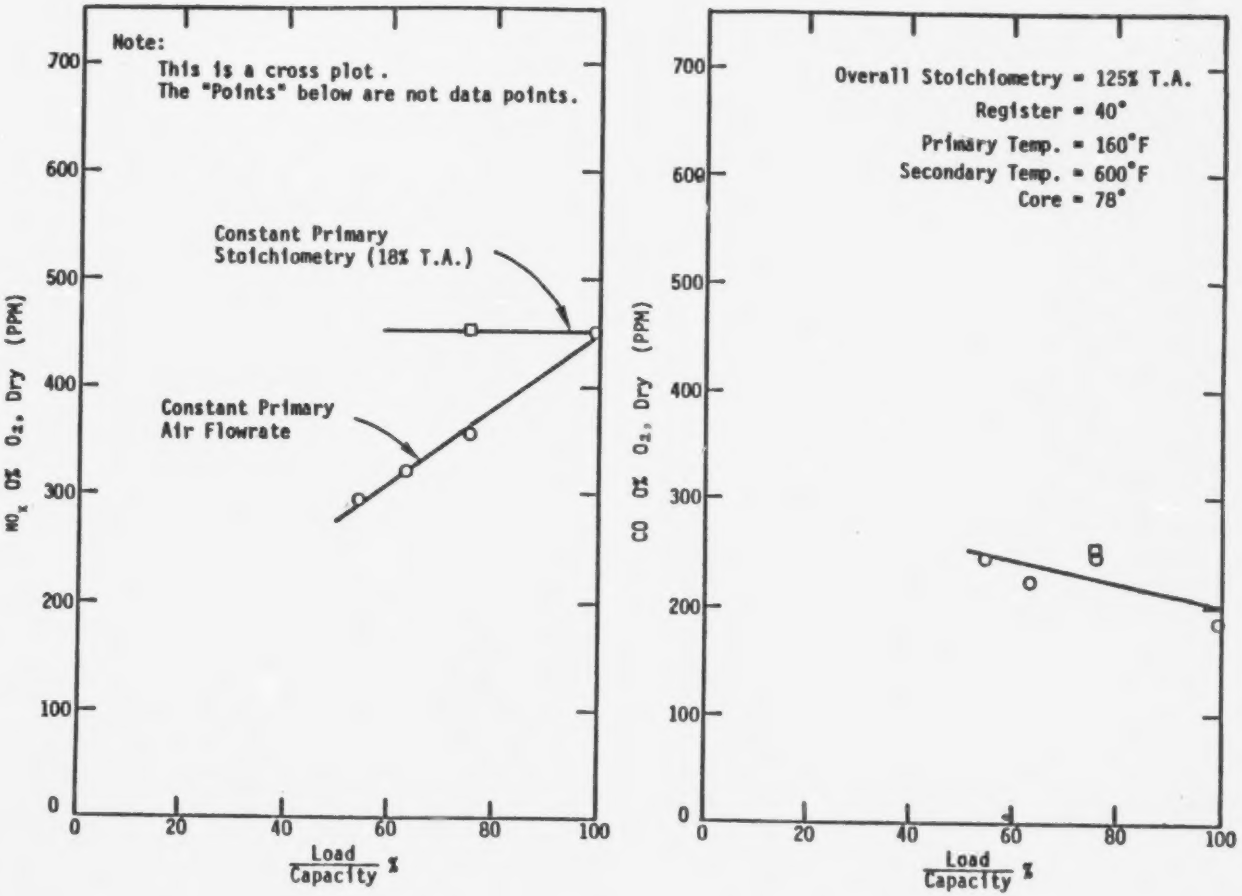


Figure 3-7. Intervane burner data: effect of load.

confirmed by testing the initial prototype DMB in the old and new LWS which have similar furnace geometry but considerably different thermal environments. These results are discussed in subsection 3.4. Thus, a "calibration factor" must be used to relate CO emissions in the old LWS to those which would be produced in a field operating boiler with different thermal environment. It should be noted that the CO emissions for the development DMBs tested in the old LWS under conditions similar to the Intervane Burner were comparable to the Intervane Burner CO emissions. This suggests that the CO emissions from DMBs operated in full scale systems would be similar to the Intervane Burner also.

The NO_x emissions for the Intervane Burner tested in the LWS were considerably lower than those measured during the baseline boiler tests. While it is possible that this difference is due in part to the same thermal environment effect that impacted CO emissions, tests with the initial prototype DMB in the old and new LWS showed essentially no impact of thermal environment on NO_x emissions. This is discussed in section 3.4. A more probable reason for the difference in NO_x emissions between the Intervane Burner and the old LWS and the baseline boiler tests is the difference in burner design and operating conditions. The average throat velocity for the Intervane Burner tested in the LWS at 80 x 10^6 Btu/hr and in the host boiler at full load are 118 and 140 ft/sec, respectively. This is due to the larger capacity of the LWS burner and its operation at less than full load. Also, in the LWS tests, the burner was set up by the Foster Wheeler service engineer with the base of the flame within the burner exit while in the field tests, the burners were adjusted to produce flames with a considerable stand off distance and premixing. The combination of lower velocities and an attached flame in the LWS tests is suspected to be responsible for lower NO_x emissions. Thus, comparisons between NO_x emissions produced by the Intervane Burner in the old-LWS and WIPCO are not valid. However, it should be noted that the NO_x emissions from the Intervane Burner tested in the old LWS are considerably greater than NO_x emissions from the development DMBs and the initial prototype DMB under similar operating conditions.

3.2 DMB Design Criteria

In EPA contract 68-02-1488, a number of DMBs were designed, constructed and tested in research furnaces. The objective was to evaluate the impacts of burner design parameters and operating conditions on performance including flame shape and stability, NO_x emissions and combustion efficiency as indicated by CO emissions. Since these tests were intended to gather data only, the burners were constructed to produce the desired fuel/air mixing rates and flame patterns in the easiest manner possible. These "development DMBs" did not use commercial burner components and were not intended or appropriate for installation in field operating boilers. For example, to provide maximum flexibility, each burner passage had an independent air supply rather than a common windbox which is the usual practice in units designed by United States manufacturers. Also, secondary air swirl was adjusted by varying the air flow rates to two-burner passages which produced different swirl levels. These streams were mixed upstream of the throat. No registers were used.

As part of this program, the data from these development DMB tests were analyzed to establish burner design and operating parameters which produced optimum performance. These parameters were then used as design criteria for the development of the prototype DMBs.

Six DMB configurations were tested in the old LWS and a smaller test facility, the old Small Watertube Boiler Simulator (old SWS). These burners ranged in capacity from 12.5 x 10^6 Btu/hr to 100 x 10^6 Btu/hr and were tested as single burners. 2x2 array of 12.5 x 10^6 Btu/hr burners (total heat input 50 x 10^6 Btu/hr) was tested also. Each burner configuration was evaluated over a range of operating conditions. The results will be discussed in terms of the following burner components:

- Fuel System
- Secondary Air System
- Tertiary Air System

3.2.1 Fuel System

The DMB fuel system includes the following geometric variables and fuel/air characteristics through the fuel nozzle:

- Primary stoichiometry
- Nozzle size and axial position
- Exit velocity
- Swirl

The effects of each variable (except nozzle size) on burner performance was evaluated. Although nozzle size has not been specifically evaluated, it is considered to have only secondary effects on burner performance over the practical range.

The DMBs tested in the research furnaces utilized a circular coal nozzle located on the burner axis. In two of the burners, there was no provision for primary swirl and as a result, the rate of mixing between the primary and secondary streams was low. This produced a long diffusion-type flame and low NO_x emissions. While long flames can be used in furnaces with sufficient flame depth where individual burner firing rates are low, they are not compatible with many smaller industrial size furnaces or larger units which utilize a smaller number of higher firing rate burners. The other DMB configurations tested in the research furnaces had impellers in their nozzles to impart swirl and increase the rate of mixing of the primary and secondary air streams. The resulting flames were considerably shorter but had slightly higher NO_x emissions. The following discussion will focus on the test results from the short flame burners since this burner configuration is most appropriate for the industrial and small utility size boilers which are the focus of this program.

Figure 3-8 shows some typical results obtained with a 50 x 10^6 Btu/hr single secondary DMB firing at full load and 125 percent theoretical air. Minimum NO_x levels are in the range of 100 ppm. CO emissions are in the range of 250-500 ppm which is considerably higher than typical burner performance in field boilers (less than 50 ppm). This difference is believed to be a consequence of the research furnace design as was discussed in the previous subsection. With the primary swirl vanes removed (axial flow) it was not possible to obtain acceptable flame stability. At 30° swirl angle an acceptable flame was achieved with minimum emissions and no measurable increase in NO_x was observed when the swirl angle was increased to 45°. Further increasing the swirl angle to 60° resulted in a large increase in NO_x emissions. Due to the limited range and scatter in the CO data, the effect of swirl angle on CO is unclear. The indicated lines represent a best judgement as to interpretation of the results. This interpretation suggests that both the fuel/air mixing characteristics and ignition characteristics are changing significantly. Therefore, there should be a design trade off between NO_x and CO with primary swirl, with lower swirl angles providing lower NO_x emissions. Ignition stability represents the lower limit of operation, although it would not be prudent to design at such a low level. Based on these and other data, it was concluded that the fuel system should be designed to produce the minimum fuel/air mixing rates commensurate with adequate flame stability and flame length constraints.

3.2.2 Secondary Air System

The DMB secondary air system includes all components which provide air through the burner throat except for the coal nozzle. Specific variables include the following:

- Air distribution between secondaries
- Velocity
- Swirl
- Burner zone stoichiometry

The DMBs tested in the research furnaces included designs with single as well as dual secondary air passages. The dual secondary design is preferred because of the additional control over fuel/air mixing rates which can be achieved by varying the flowrates and swirl in the two secondary air passages. However, for simplicity, four of the DMBs were designed with a single secondary air passage.

Figure 3-9 shows the effects of secondary air system variables on the performance of a single secondary 50 x 10^6 Btu/hr burner. The operating conditions were the same as for the data presented in Figure 3-8 and the primary swirl was 45°. Variations in burner zone stoichiometry are produced by varying the amount of air through the outboard tertiary air passages. For burner zone stoichiometry equal to the overall stoichiometry (125 percent theoretical air) all of the air passes through the burner throat (unstaged condition). Figure 3-9 shows that for unstaged conditions the DMB produces NO_x and CO emissions of 400 and 300 ppm, respectively. As the burner zone stoichiometry is decrease by diverting air to the tertiary air ports, keeping the overall stoichiometry constant at 125 percent theoretical air, NO_x emissions decrease. At a burner zone stoichiometry of 60 percent theoretical air, the range of NO_x emissions is 90 to 180 ppm. CO emissions remain essentially constant down to a burner zone stoichiometry of about 70 percent theoretical air where the air flow through the secondary air passages has decreased to the point where flame stability has deteriorated and CO emissions rise. While the flame is still stable initially, continued reduction in burner zone stoichiometry leads eventually to instability and flame out. Due to the onset on this instability, operating near the knee of the CO curve is unacceptable. For this burner, operation at 70 percent theoretical air burner zone stoichiometry appears to be acceptable. Under this minimum condition, NO_x emissions at 0 percent O_2 are about 150 ppm.

In comparing the NO_x and CO characteristics, note that the impact of burner zone stoichiometry on NO_x emissions remained unchanged even as the CO emissions markedly increased. This suggests that the NO_x formation is being controlled principally by the burner zone stoichiometry and not by the primary/secondary air mixing rates. The conditions producing the increase in CO emissions illustrated in Figure 3-9 were found to be strongly dependent on the burner settings as well as the design velocity. In fact, at full load, it was possible to obtain minimum CO and NO_x emissions over a wide range in excess air levels by varying burner zone stoichiometry and swirl conditions

14.6 Thermal MW (50 x 10^6 Btu/hr) Single Secondary DMB
Coal: Utah Bituminous
Load: 14.1 Thermal MW (48 x 10^6 Btu/hr)
Overall Stoichiometry: 125% TA
Secondary Swirl Vanes: 45°

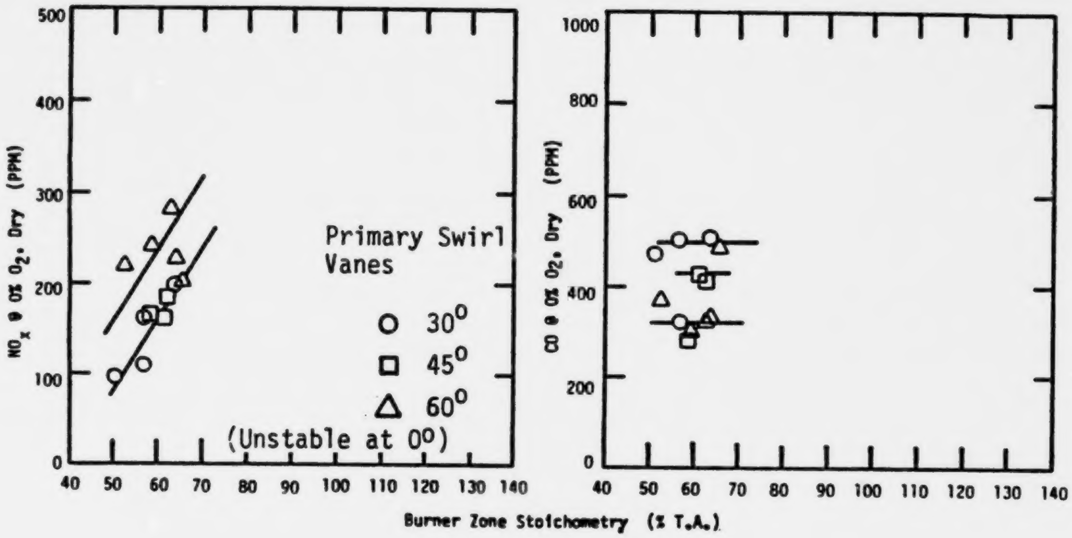


Figure 3-8. Effects of fuel system variables on DMB performance.

14.6 Thermal MW (50 x 10^6 Btu/hr) Single Secondary DMB
Coal: Utah Bituminous
Load: 14.1 Thermal MW (48 x 10^6 Btu/hr)
Overall Stoichiometry: 125% TA
Primary Swirl Vanes: 45°

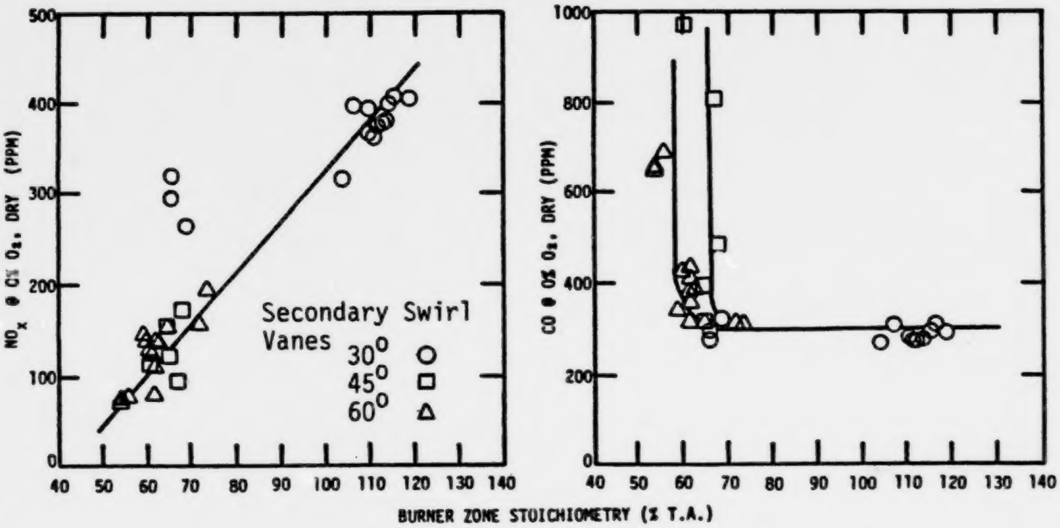


Figure 3-9. Effects of secondary air system variables on DMB performance.

together. However, this type of burner control would be difficult to implement in commercial systems. Commercial burners are expected to operate with acceptable performance over a range of excess O_2 without adjustment. Although not shown in Figure 3-9, at zero swirl the flame could not be operated stabily even at high burner zone stoichiometry and flame out resulted. This is not surprising and is typical performance even for commercial burners. As the secondary swirl was increased to 30° it was possible to achieve a stable flame over a burner zone stoichiometry range from 70 percent theoretical air to essentially unstaged conditions (120 percent theoretical air). Lower burner zone stoichiometries were possible with increased secondary swirl angle. Note that the NO_x characteristics were essentially unchanged with secondary swirl angle while the CO emissions were improved by increasing secondary swirl. Thus, there is a trade off in NO_x and CO emissions as burner zone stoichiometry and swirl are varied. Optimum values with this burner for fixed operating conditions are a secondary swirl angle of 30-45° and a burner zone stoichiometry of 60 percent theoretical air.

3.2.3 Tertiary Air System

The DMB tertiary air system includes all components which provide air through the tertiary air passages. The specific variables include the following:

- Velocity
- Number of ports
- Location of ports

Variations in tertiary velocity have been found to have little effect on NO_x and CO emissions for tertiary air port configurations of practical significance. However, the number and location of the tertiary air ports have been found to affect CO but not NO_x emissions. Figure 3-10 shows some results from tests of a 4-burner array of 12.5 x 10^6 Btu/hr DMBs. Based on four tertiary air ports per burner, the 4-burner array should have a total of 16 tertiary air ports. However, to minimize the number of ports, ports for

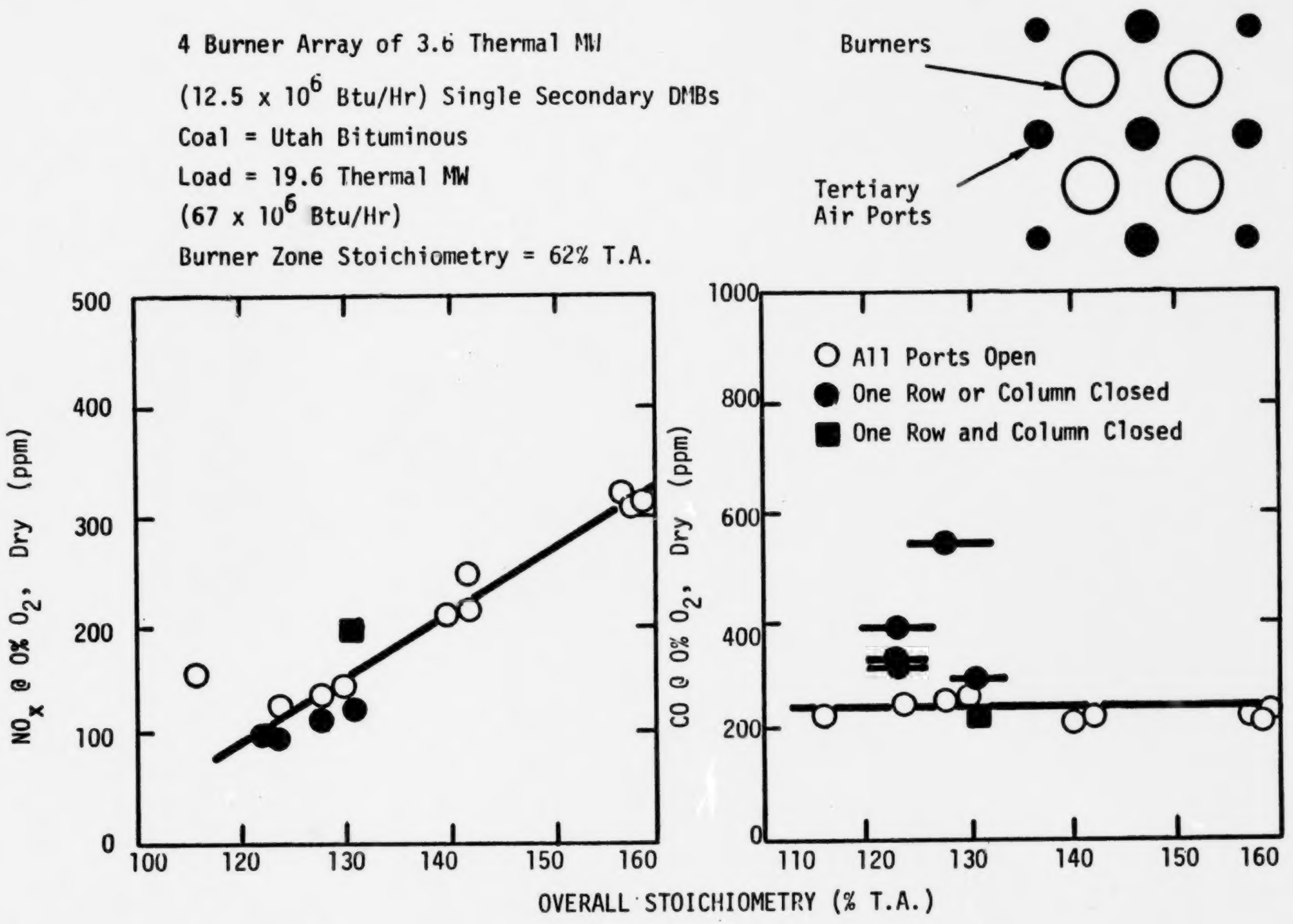


Figure 3-10. Effects of tertiary air system variables on DMB performance.

adjacent burners were combined as shown. Tertiary air port areas were adjusted so as to maintain constant tertiary air port velocity. Thus, the center air port has an area 4 times that of a corner air port, etc. Tests were conducted by maintaining the secondary air flowrate (burner zone stoichiometry) constant and varying the tertiary air flowrate (overall stoichiometry) and the number of ports in service. The decrease in NO_x emissions as the overall stoichiometry was reduced is typical of performance for most burners. The CO emissions for all ports in service are constant, independent of overall stoichiometry over the range tested. Although not shown in Figure 3-10, lower values of overall stoichiometry less than 110 percent theoretical air caused a sharp increase in CO and smoke emissions. This is typical of most burners including the Intervane Burner as discussed in the previous section.

In addition, tests were conducted with various rows and/or columns of tertiary air ports out of service to define the sensitivity of NO_x and CO emissions to the number and location of the tertiary air ports. The results presented in Figure 3-10 show that within experimental accuracy, the NO_x characteristics were unaffected by variations in tertiary air velocity and port location. The general conclusion is that for these short flame burners the NO_x formation depends primarily on the conditions within the fuel rich combustion zone and thus the details of the tertiary air port configuration are not of key importance. While NO_x emissions were essentially unaffected by tertiary air port locations in the multi-burner configurations, CO emissions were strongly impacted. Note that unsymmetric changes in tertiary air ports out of service were accompanied by a significant increase in CO emissions. This shows that the tertiary air port locations have a strong impact on the overall mixing in the lower furnace and subsequent burnout of combustibles. Improper port location may result in incomplete CO burnout and excessive carbon loss. If this occurs, the burner zone and/or overall stoichiometries must be increased. This will increase NO_x emissions.

3.2.4 DMB Requirements

The optimum design parameters for DMBs cannot be defined independent of the design of the burner components and the specific furnace application. For example, the development DMBs all utilized a central coal nozzle with swirl vanes to control fuel/air mixing rates. However, Foster Wheeler's coal nozzle design is an annulus with tangential inlet flow. Also, the furnace exit geometry and tertiary air port array will need to be adjusted to conform to the burner to burner spacing, windbox depth and other furnace design constraints.

The DMB design criteria listed in Table 3-4 have been assembled recognizing these considerations. A nominal design point has been specified based directly on the analysis of the development DMB data presented in the previous subsection. Also, a testing range has been established for optimization of the burner design for a specific application. In many cases, the nominal design parameters will be Site Dependent (S.D.).

The design of the fuel system has a pronounced impact on both flame stability and NO_x emissions. The primary air temperature and stoichiometry will be dictated by the design and operating parameters of the coal pulverizer (S.D.). Typical values are 150°F and 18-25 percent theoretical air for the temperature and stoichiometry, respectively. Optimum primary velocity is in the range of 75 ft/sec with the minimum swirl commensurate with flame stability and length constraints. For a burner with a non-central coal nozzle, a DMB should be designed with considerable flexibility in this area.

The secondary air system also impacts flame stability and NO_x emissions. The secondary air temperature will be determined by air heater design and will be in the range of 600°F for most applications. The key secondary air system parameter is the burner zone stoichiometry which should be in the range of 50 to 70 percent T.A.. The development DMB data do not exhibit the characteristic minimum in NO_x emissions with increases for both higher and lower burner zone stoichiometries that have been observed with several other

TABLE 3-4. DISTRIBUTED-MIXING BURNER DESIGN PARAMETERS

Parameter	Nominal Design Point	Testing Range
Fuel System		
Primary Temperature (^oF)	S. D.	130-180
Primary Stoichiometry (% T.A.)	S. D.	17-30
Primary Velocity (ft/sec)	75	50-90
Primary Swirl	45^o Vanes	Variable
Air System		
Secondary		
Temperature (^oF)	S. D.	400-650
Burner Zone Stoichiometry (% T.A.)	50-70	40-120
Inner Swirl	Variable	Variable
Outer Swirl	Variable	Variable
Axial Velocity (ft/sec)	60	50-90
Inner/Total Area	0.33	Variable
Inner/Total Flow Rate	0.33	Variable
Tertiary		
Temperature (^oF)	S. D.	400-650
Swirl	None	—
Axial Velocity (ft/sec)	50	40-60
Angle (degrees)	0	—
Number	4	—
Location (radius/throat diameter)	1.8	S. D.
Divergence (degrees)	0	—
Exit		
Half Angle (degrees)	25	Variable
Length/Diameter	0.4	S. D.
Setback - Inner Secondary (inches)	0	Variable
Setback - Outer Secondary (inches)	0	Variable
Operational Variables		
Capacity (10^6 Btu/hr)	S. D.	—
Turndown (% capacity)	S. D.	≈50
Overall Stoichiometry (% T.A.)	S. D.	100-150

combustion systems. However, combustion efficiency and flame stability decrease at very fuel rich conditions and this establishes the optimum value: the lowest burner zone stoichiometry commensurate with adequate flame stability and combustion efficiency. Two secondary air passages are preferred because of the additional flexibility in tailoring the fuel/air mixing rates. The swirl in each passage should be adjustable and in commercial burners this will probably be achieved via registers. The development DMBs had two equal secondary air passage areas with equal velocities and flow rates. This resulted in a smaller annular passage width for the outer secondary. A 2/1 ratio of outer to inner secondary area is preferred to balance the passage widths. The optimum secondary air velocity is about 60 ft/sec.

The tertiary air system has only minimal impact on NO_x emissions but can significantly impact combustion efficiency. The tertiary air will be drawn from the windbox at the same temperature as the secondary air. An axial velocity of 50 ft/sec is optimum. The most important tertiary air system design consideration is to arrange the ports so as to: (1) maximize the size of the fuel rich primary combustion zone, (2) avoid contact of the fuel rich combustion products with furnace walls and (3) mix the tertiary air uniformly with the combustion products exiting the primary zone. In the development DMB tests, good results were obtained for tertiary air ports spaced uniformly around each burner at a radial distance equal to 2.2 x the throat diameter. This should be used as a starting point for a new burner design recognizing that modifications may be necessary due to furnace design constraints.

The design of the burner exit will need to be selected based on the design of the burner components and furnace/windboxes constraints. For the development DMBs relatively long (deep) exits were used with a divergence angle of 25°. Long exits tend to promote flame stability. However they are not compatible with short windbox depths or narrow burner-to-burner spacings. If a short exit is required, it may be necessary to increase the rate of fuel/air mixing to restore flame stability. This will increase NO_x emissions somewhat.

3.3 Initial Prototype DMB

The initial prototype DMB for the industrial boiler demonstration at WIPCO was designed by integrating the DMB design criteria and host boiler characteristics with Foster Wheeler burner components. In many cases, the data from the development DMB tests were not sufficient to clearly define optimum parameter values. Thus, these criteria are nominal and were used as the starting point for prototype burner testing and optimization. The prototype DMB was designed to be flexible to permit many of these parameters to be varied during testing. The test burner also incorporated integral controls and flowmeters to permit the control and measurement of air flow rates through each burner passage in a common windbox application, such as the demonstration site. These internal windbox devices were calibrated for use in both the prototype burner and the burners to be installed at the WIPCO boiler. The calibrations of the internal flowmeters used during the prototype burner tests and in the field demonstration are discussed in Appendix E.

The initial DMB design was evaluated under both unstaged and staged combustion conditions in the old LWS. The objective of the unstaged tests was to verify that the DMB could operate unstaged if a problem with the tertiary air system were to develop at the WIPCO demonstration site. The staged tests were intended to optimize performance with the available adjustable parameters and achieve an optimum balance of stability, efficiency, and emissions.

The prototype burner tests were initiated in December 1979. Shortly after testing began, the LWS furnace walls deteriorated and testing was halted. These initial tests utilized the baseline Utah coal and were primarily directed toward evaluation of burner performance unstaged. Only brief staged tests were conducted. Testing under both staged and unstaged conditions resumed after the LWS furnace was rebuilt. The design of the two LWS configurations are detailed in Appendix B. The major difference is the addition of refractory insulation in the new LWS to produce a thermal environment more representative of field boilers.

The following subsection presents the design of the initial prototype DMB. The unstaged and staged test results are presented in subsections 3.3.2 and 3.3.3 respectively.

3.3.1 Initial Prototype DMB Design

The initial prototype DMB integrated the EPA DMB design criteria and the host boiler criteria into a commercial burner design. The nominal DMB design criteria which were listed in Table 3-4 represent the starting point for the initial burner optimization. Characteristics of the host site, WIPCO Pearl Station, and Foster Wheeler burner hardware required compromising several parameters.

The Pearl Station characteristics were compatible with the DMB design criteria with the following exceptions:

- Windbox depth and burner exit length
- Throat diameter
- Burner spacing and structure constraints

The windbox of the WIPCO boiler was designed to accommodate the original equipment, pre-NSPS Intervane Burners. The windbox geometry with the Intervane Burner is shown in Figure 3-11. The single register and short exit design of these burners provided ample space for combustion air to flow around the burner components. However, the windbox depth is insufficient to contain the dual registers and exit length specified in the DMB design criteria. The installation of a DMB strictly matching the design criteria in the WIPCO windbox is illustrated in Figure 3-12. The two register assemblies and large exit would occupy essentially the entire windbox. Foster Wheeler determined that the resulting blockage would prevent adequate and uniform flow to the burners. The maximum exit length which could be used corresponds to about 40 percent of the length specified by the DMB criteria.

The lower secondary air velocities specified by the DMB criteria required a larger throat and exit diameters than for the high turbulence

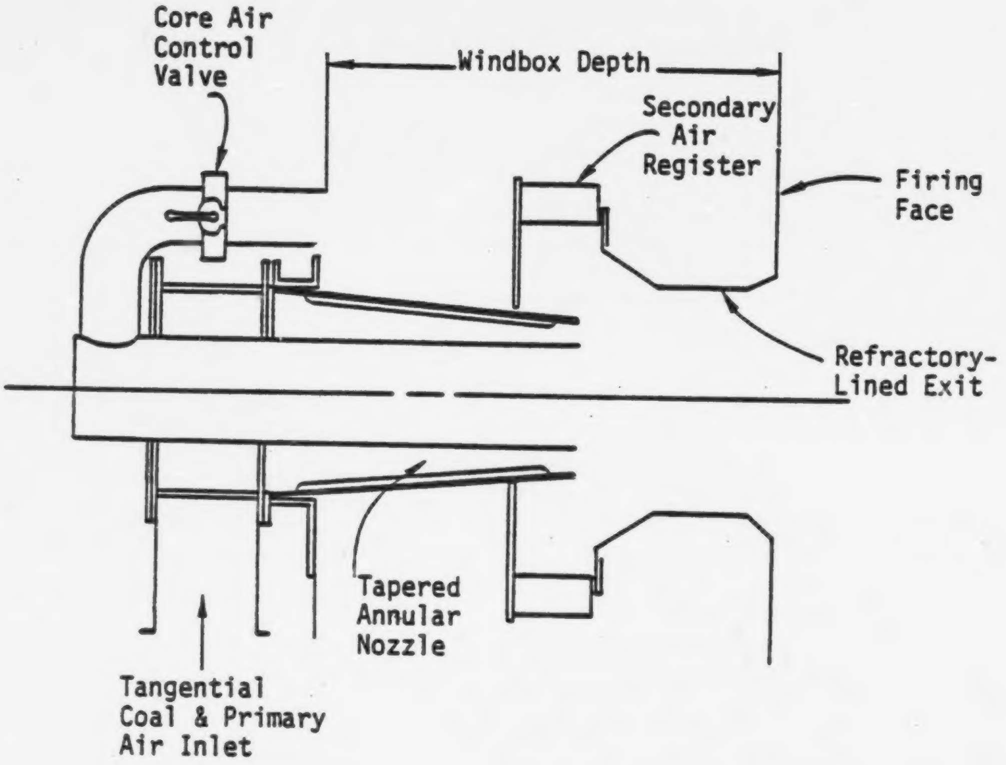

Core Air
Control
Valve
Windbox Depth
Secondary
Air
Register
Firing
Face
Refractory-
Lined Exit
Tapered
Annular
Nozzle
Tangential
Coal & Primary
Air Inlet

Figure 3-11. Foster Wheeler intervane burner.

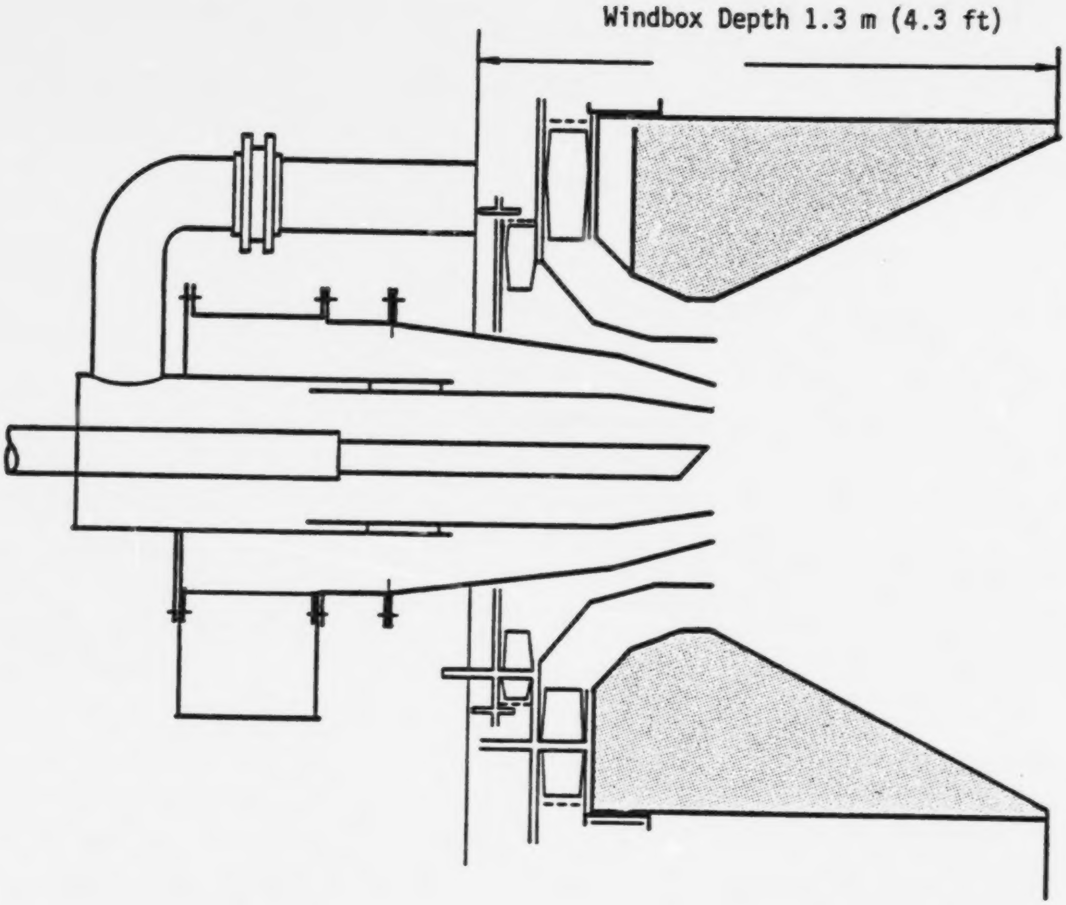

Windbox Depth 1.3 m (4.3 ft)

Figure 3-12. DMB meeting design criteria in WIPCO windbox.

Intervane Burner. Since the burner throat was formed by a thin layer of refractory over bent water-wall tubes, there was no way to accommodate the DMB throat without modifying the boiler tube wall. The arrangement of the Intervane Burners on the front wall, shown in Figure 3-13, spaces the burners too close for the tertiary ports to be located according to the design criteria. In addition, windbox and furnace structural considerations limit the potential tertiary port locations. The spacing of the burners at Pearl Station, however, was used in determining the location of the tertiary air ports for the prototype DMB test configuration, shown in Figure 3-14. Note that the tertiary ports are spaced further apart horizontally than vertically, matching the WIPCO arrangement.

Figure 3-15 is a cross-sectional view of the prototype burner showing its design details. The following Foster Wheeler commercial burner components have been incorporated into the design:

- Annular Coal Nozzle with Tangential Inlet
- Telescoping Coal Nozzle for Primary Velocity Control
- Two Parallel Secondary Air Registers for Swirl Control & Flow Shutoff
- Air Hoods for Secondary Flow Rate Control and Measurement
- Commercial Flame Scanning and Ignition System

The coal and primary air enter the annular coal nozzle through a tangential inlet to provide swirl. The coal nozzle is a tapered annulus. The exit end of the coal nozzle is formed from two concentric cones. The inner cone can be moved axially to vary the exit area, and hence, the primary velocity. The outer portion of the coal nozzle is constructed of removable sections so that the overall length of the coal nozzle may be changed to vary the nozzle setback within the burner throat. There are two concentric secondary air passages supplied from a common windbox. Each is equipped with an adjustable

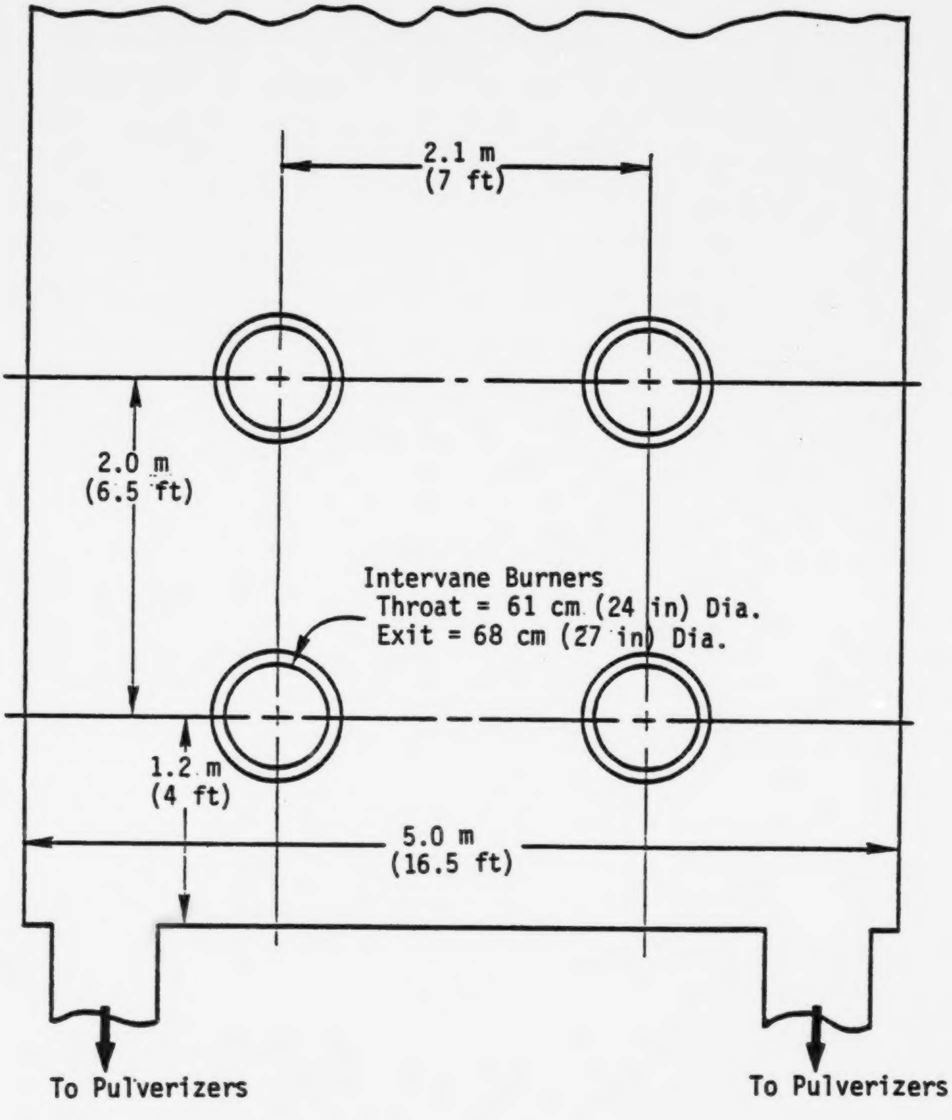

2.1 m
(7 ft)
2.0 m
(6.5 ft)
Intervane Burners
Throat = 61 cm (24 in) Dia.
Exit = 68 cm (27 in) Dia.
1.2 m
(4 ft)
5.0 m
(16.5 ft)
To Pulverizers
To Pulverizers

Figure 3-13. Original WIPCO burner arrangement.

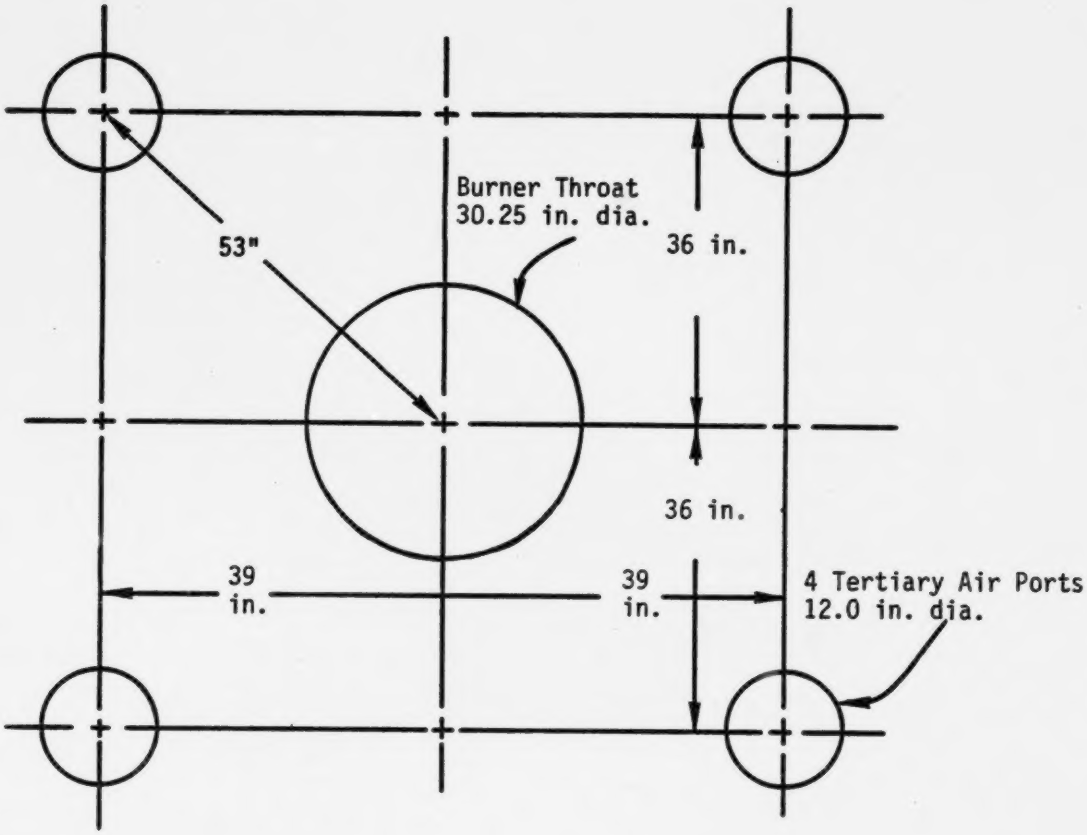

Burner Throat
30.25 in. dia.
53"
36 in.
36 in.
39 in.
39 in.
4 Tertiary Air Ports
12.0 in. dia.

Figure 3-14. Tertiary port arrangement for the initial prototype DMB.

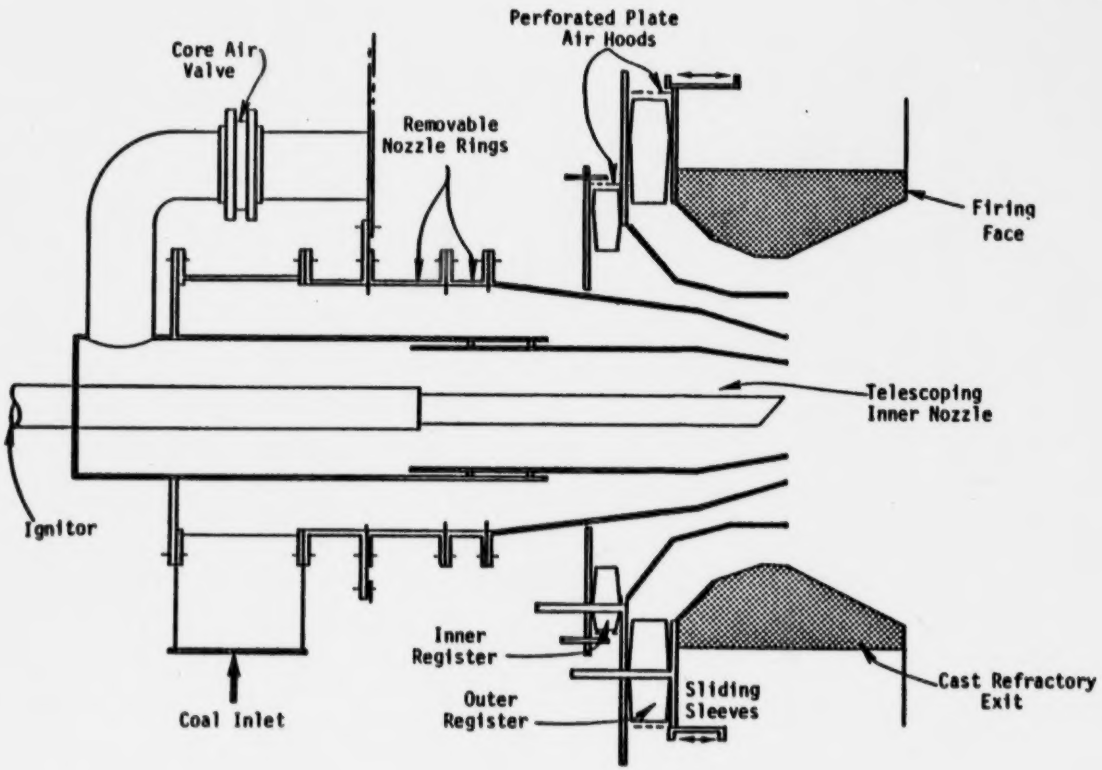

Core Air Valve
Removable Nozzle Rings
Perforated Plate Air Hoods
Firing Face
Telescoping Inner Nozzle
Ignitor
Inner Register
Outer Register
Sliding Sleeves
Cast Refractory Exit
Coal Inlet

Figure 3-15. Cross-section of industrial prototype burner based on Foster Wheeler design, without tertiary air ports.

register for swirl control, an axially movable sleeve for flow control and a perforated plate (air hood) for flow rate measurement. Pressure taps on both sides of each perforated plate allow the pressure drop to be measured and correlated with sleeve position and flow rate.

The portion of the burner inside the coal nozzle is termed the core, and is supplied with a small amount of cooling air from the windbox. A retractable ignition system, including spark ignition, a 10 x 10^6 Btu/hr oil gun and an ignition flame scanner are located in the core on the burner centerline. The main flame scanner views the flame through the inner secondary air passage.

Tertiary (staging) air is supplied from the windbox through outboard tertiary air ports. During testing in the research facilities the airflow rate through each port was controlled and measured by the assembly shown in Figure 3-16. The hemispherical poppet pivots to vary the open area, and thus, control the flow rate. The pressure drop across the perforated plate air hood provides an indication of flow rate.

The prototype burner was designed with "flexible" parameters to permit the flow rates, velocities and swirl in the burner passages to be varied to optimize burner performance. The following burner parameters were adjustable on the prototype burner:

- Inner Register
- Outer Register
- Inner Sleeve
- Outer Sleeve
- Core Air Valve
- Nozzle Setback
- Primary Exit Area
- Tertiary Exit Area

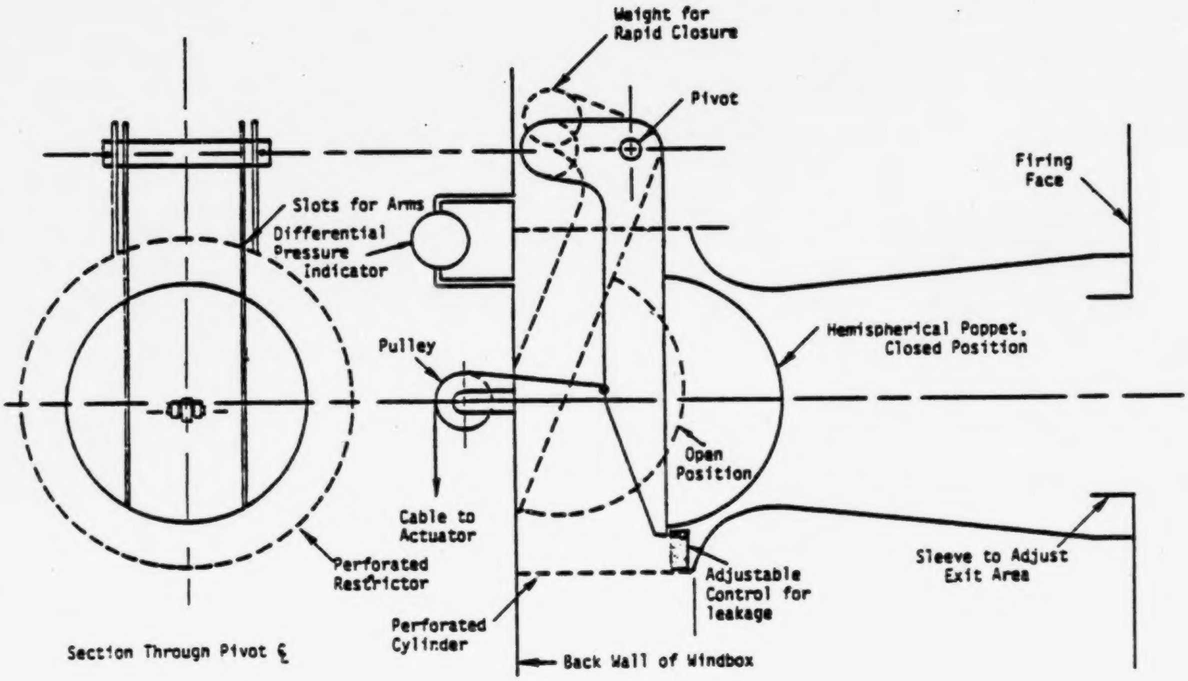

Weight for Rapid Closure
Pivot
Firing Face
Slots for Arms
Differential Pressure Indicator
Hemispherical Poppet, Closed Position
Pulley
Open Position
Cable to Actuator
Perforated Restrictor
Adjustable Control for leakage
Sleeve to Adjust Exit Area
Perforated Cylinder
Section Through Pivot ℄
Back Wall of Windbox

Figure 3-16. Tertiary port control valve.

The dimensions and ranges of adjustment are listed in Table 3-6. All of the dimensions listed match the prototype design point except the exit length and tertiary port locations as previously discussed.

3.3.2 Unstaged Tests of the Initial Prototype DMB in the Old LWS

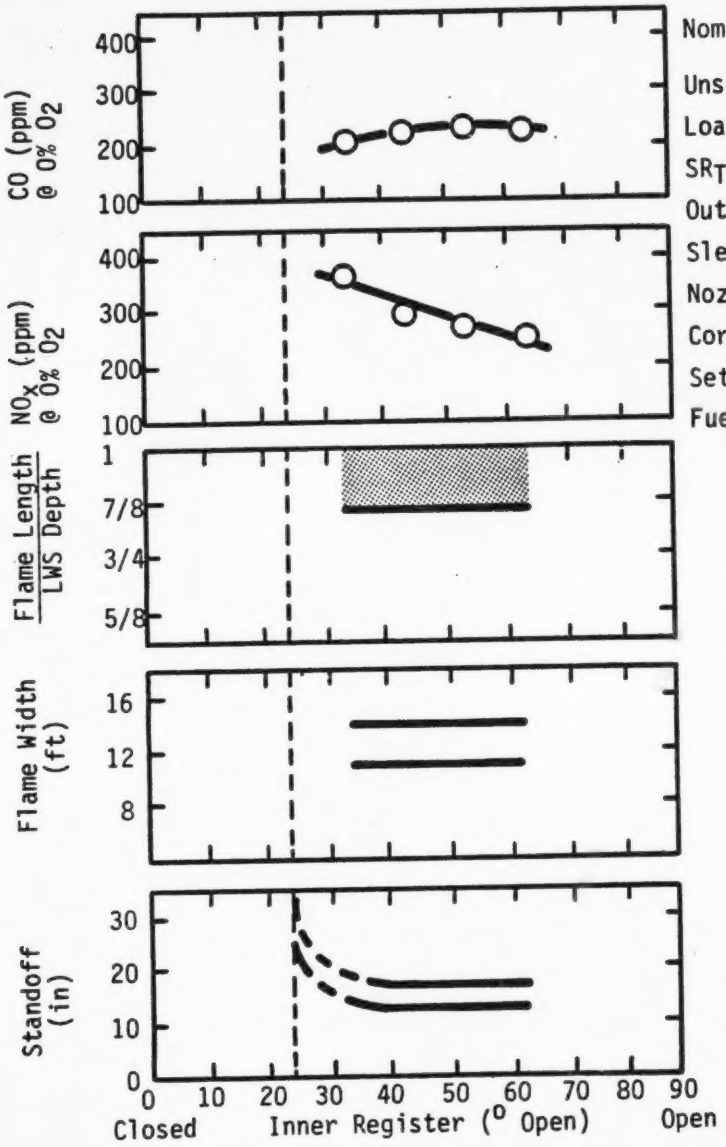
The initial prototype burner was fired over the host boiler operating range to verify that the DMB could operate unstaged if problem with the tertiary air system developed at WIPCO. The prototype burner was fired over ranges of burner settings, load, and excess air with Utah 1 coal to allow direct comparison with previous development DMB and Intervane burner test results in the original LWS. The test conditions were adjusted to match the WIPCO unit load schedule. The load schedules for all four burners in service, based on boiler design specifications, and for two burners in service, from results of a single mill test, were shown in Figure 2-7. Since the host boiler normally operates with all burners in service, the boiler design specifications were used in these tests.

The effect of inner register position on unstaged burner performance is shown in Figure 3-17. Increasing the degree of swirl by closing the register resulted in an increase in NO_x emissions until a loss of flame at less than 35 degrees open. Flame shape and stability were not measurably affected by the degree of swirl within the normal operating range. The rise in NO_x emissions was commensurate with the expected behavior since increased swirl generally results in more rapid and complete fuel and air mixing, which is known to produce higher levels of NO_x. The loss of flame at high swirl levels, however, is not consistent with this explanation. The high swirl setting, achieved by closing the register vanes, probably causes increased flow restriction through the secondary air passage. This increased resistance to flow forces air to the outer secondary air passage (which is larger) and reduces the tangential momentum which stabilizes the flame. From these results, a position of 45 degrees open was identified as the most satisfactory inner register setting since it allowed sufficient swirl for flame stabilization while producing an acceptable pressure drop across the inner register.

TABLE 3-5. INITIAL PROTOTYPE BURNER DIMENSIONS AND ADJUSTMENTS

Design Variable	Nominal* Value	Adjustment	
		Range	Method
Fuel Injector			
Core Diameter (in)	9.75		
Core Area (in^2)	74.7		
Nozzle Diameter (in)	14.5		
Annulus Thickness (in)	2.375	1.7-3.3	Telescoping Nozzle
Primary Area (in^2)	90.5	68-136	
Setback (in)	0	-2 - +2	Remove/Replace Nozzle Rings
Inner Secondary Channel			
Outer Diameter (in)	20.75	Variable	Replace Secondary Divider
Annulus Thickness (in)	3.125	Variable	
Area (in^2)	173.0	Variable	
Setback (in)	0	Variable	
Outer Secondary Channel			
Outer Diameter (in)	30.25	Variable	Recast Exit
Annulus Thickness (in)	4.75	Variable	
Area (in^2)	380.5	Variable	
Setback (in)	0	Variable	
Tertiary Ducts			
Distance from Burner ℄ (in)	53	Variable	Modify Windbox
Spacing around Burner (deg.)	90	Variable	
Number of Ports	4		
Injector Angle (deg.)	0		
Axial Position (in)	0		
Diameter (in)	13.25	Variable	Sleeve
Total (in^2)	553	Variable	
Throat and Exit			
Throat Diameter (in)	30.25	Variable	Recast Exit
Throat Area (in^2)	718.7	Variable	
Half Angle of Exit (deg.)	25	Variable	
Length of Exit (in)	12	Variable	
Length/Diameter	0.40	Variable	

* 1.0 in = 2.54 cm
1.0 in^2 = 6.45 cm^2



Nominal Conditions

Unstaged

Load = 70 x 10^6 Btu/hr

SR_T = 123% TA

Out Reg = 55° Open

Sleeves = 100% Open

Nozzle = 3 in

Core = 45°

Setback = 0

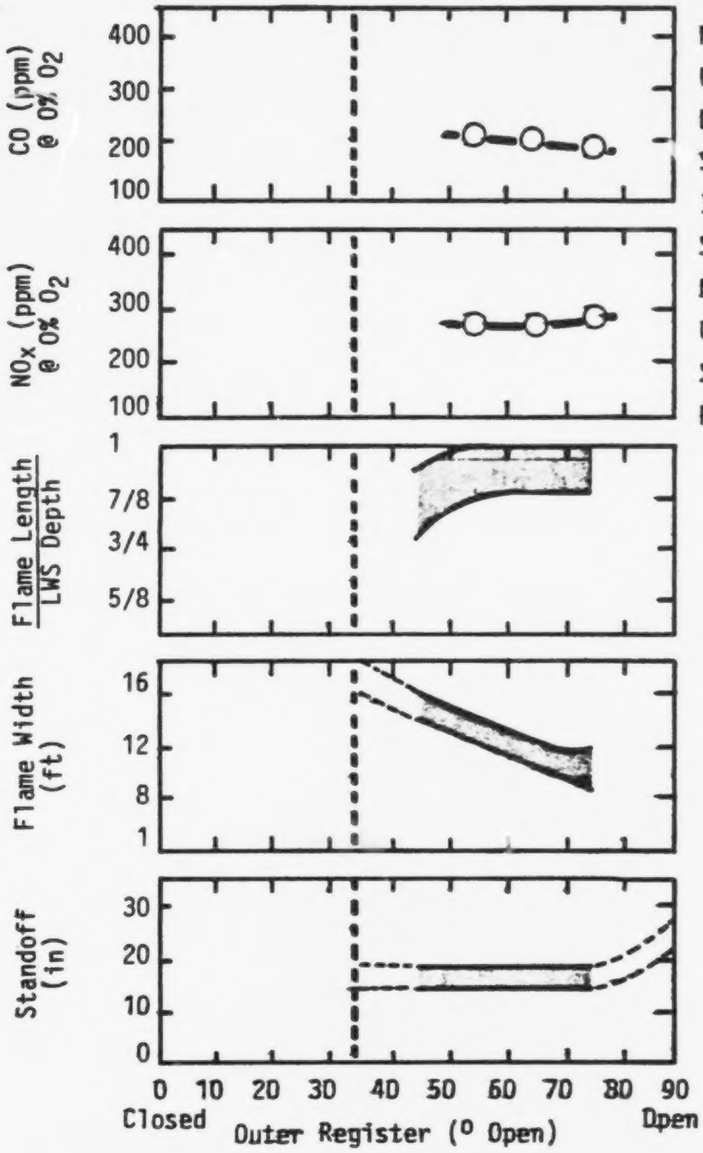
Fuel = Utah Bituminous

Figure 3-17. Effect of inner register position on the unstaged performance of the initial prototype DMB.

In contrast to the inner register, the outer register had a pronounced effect on flame shape but little effect on emissions (see Figure 3-18). Increasing the outer swirl produced a shorter, wider flame until the flame became attached to the furnace wall adjacent to the quarl with the register vanes at 35 degrees open. Once the flame was wall-attached, it was necessary to open the outer register to 75 degrees in order to effect a transition back to the normal condition. Opening the outer register, and thus reducing swirl, past the 75 degrees position resulted in a loss of flame. Loss of flame stability at low outer swirl is attributed to the same mechanism that resulted in the flameout at high inner swirl. As the outer swirl is decreased, the outer secondary flow restriction decreases, which diverts more air from the high swirl inner secondary until insufficient tangential momentum remains to stabilize the flame at the burner exit.

The minimal effect of outer register position on emissions suggests that the outer secondary air does not mix with the primary and inner secondary air until after the NO_x has been substantially formed. Two operating points were identified for further testing. An outer register setting of 55 degrees resulted in a more desirable flame shape, but wall-attached flames were occasionally observed at that setting. Seventy Five degrees was also selected since this was the highest swirl setting at which there was no indication of a wall-attached flame.

Having evaluated both registers, the next step was to determine the effect of the burner air sleeves. The effect of the outer sleeve is shown in Figure 3-19. Beginning with the sleeve fully open, closing the sleeve to 75 percent open had no effect on emissions, but caused the flame to become narrower. Further closing of the sleeve to 50 percent open resulted in a loss of flame. The narrower flame with the partially closed sleeve is due to diversion of air from the outer air envelope to the flame interior. This also causes an increase in the inner secondary velocity until the flame is pushed away from the burner. It was determined at this time that further characterization of the outer sleeve required an increase in the inner swirl both to hold the flame close to the exit and to counteract the air diversion caused by closing the outer sleeve.



NOMINAL CONDITIONS:

Unstaged

Load = 70 x 10^6 Btu/hr

SR_T = 123% TA

Inn. Reg. = 45° Open

Sleeves = 100% Open

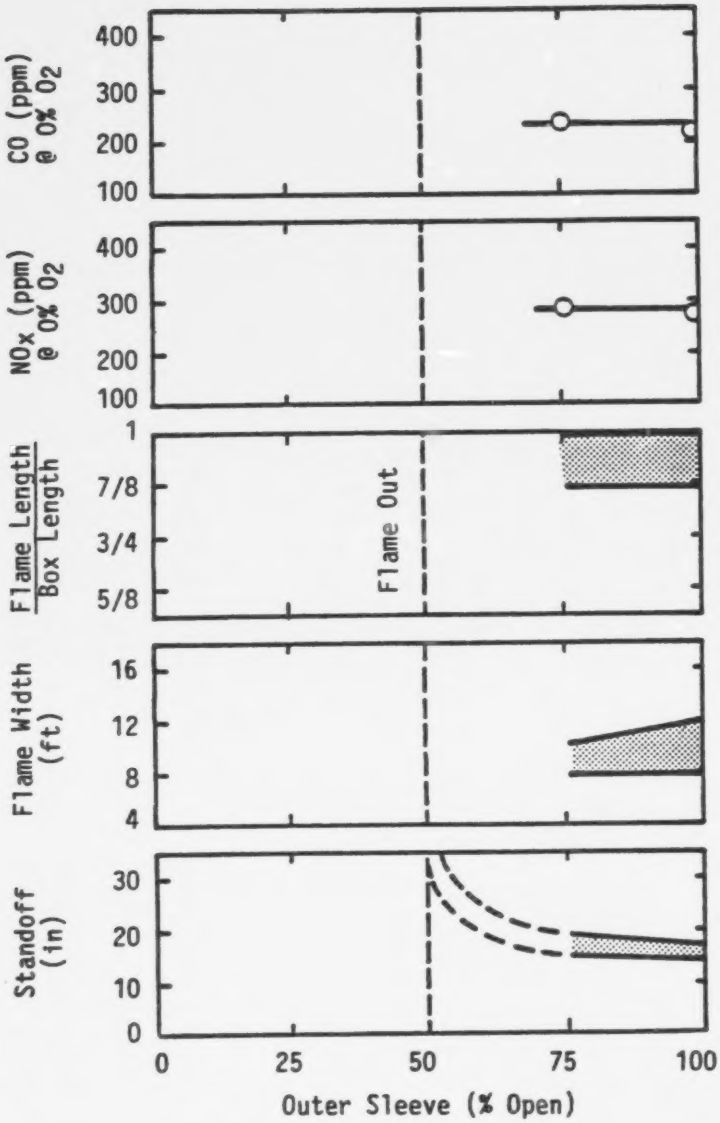
Nozzle = 3 in.

Core = 45°

Setback = 0

Fuel = Utah Bituminous

Figure 3-18. Effect of outer register position on the unstaged performance of the initial prototype DMB.



UNSTAGED

Load = 70 x 10^6 Btu/hr

SR_T = 123% TA

In Reg = 45° Open

Out Reg = 75° Open

In Sleeve = 100% Open

Nozzle = 3 In.

Core = 45°

Setback = 0

Fuel = Utah Bituminous

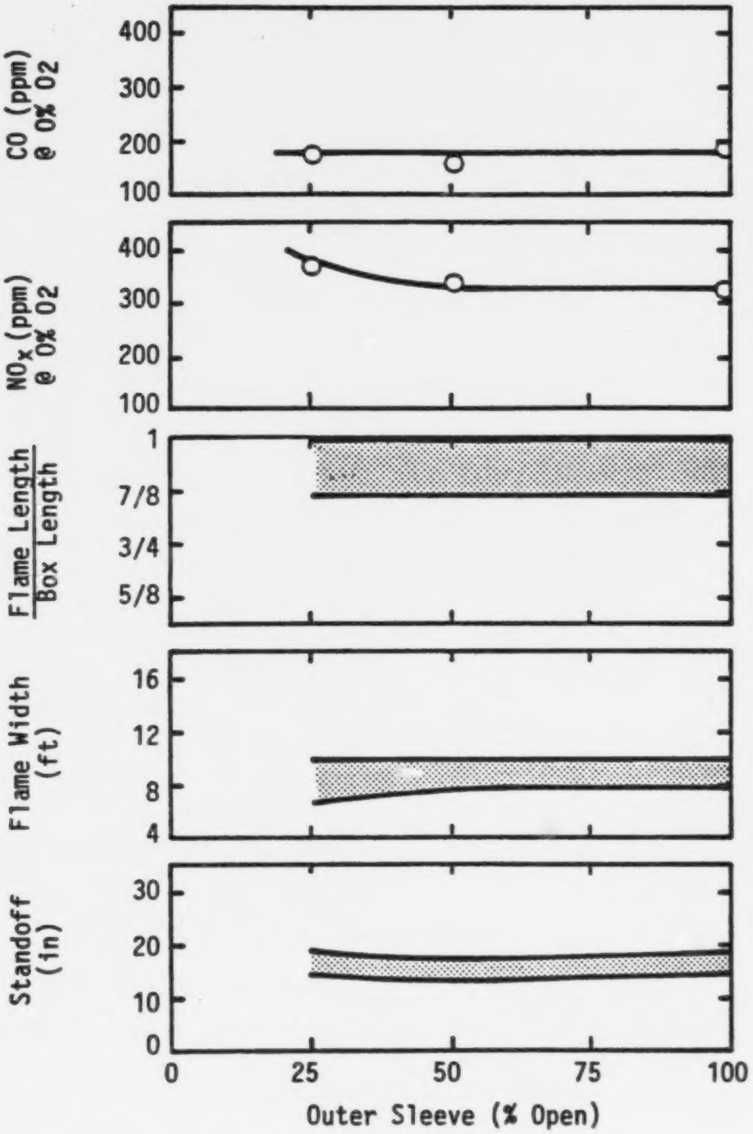
Figure 3-19. Effect of outer sleeve position on unstaged performance of the initial prototype DMB with the inner register at 45° open.

With the inner register setting at 35 degrees open it was possible to close the outer sleeve to 25 percent open without causing a loss of flame. The test results are summarized in Figure 3-20. Under these conditions the only effect of the outer sleeve was to increase the NO_x emissions. This was attributed to the increased air flow rate in the high swirl inner secondary resulting in rapid fuel/air mixing at the burner exit. The flame width was only a slightly affected by the outer sleeve position. The 100 percent open position was selected as the most satisfactory operating condition primarily because it allowed maximum flexibility in operation and produced a lower burner pressure drop.

Table 3-6 summarizes the ranges of burner variables investigated and their effects and lists the operating point selected for the variable load tests. The burner was tested over a 70 to 100 x 10^6 Btu/hr load range using the host boiler operating conditions which were in Figure 2-7. The results of these tests, shown in Figure 3-21, exhibit no influence of load on NO_x emissions except for the 70 x 10^6 Btu/hr case. This is similar to the Intervane Burner performance as shown in Figure 3-22. The test results for both burners show that NO_x is independent of load where the primary stoichiometry increases with decreasing load. It is suspected that this is actually an effect of primary velocity, which influences the primary/ secondary mixing rates, rather than primary stoichiometry.

Another important observation can be made from Figure 3-22. Note that at the overall stoichiometry employed for the majority of the test (123 percent T.A.) the burner is operating in the "knee" region of the CO curve. Therefore slight variations in the stoichiometry, which might be caused by disturbances in coal feed rate, or other perturbations, could cause the operating point to shift around the knee. This may partially explain the spontaneous flameouts, transitions to wall-attached flames and inconsistent flame shapes observed throughout the test series.

These observations indicated that a change in burner parameters was required. The stability problem and the observation of a 15 to 16-inch flame standoff suggested that changing the primary setback might be advantageous



Unstaged
Load = 70 x 10^6 Btu/hr
SR_T = 127% TA
In Reg = 35° Open
Out Reg = 75° Open
In Sleeve = 100% Open
Nozzle = 3 in.
Core = 45°
Setback = 0
Fuel = Utah Bituminous

Figure 3-20. Effect of outer sleeve position on unstaged performance of the initial prototype DMB with the inner register at 35° open.

TABLE 3-6. SUMMARY OF BURNER VARIABLES ON UNSTAGED PERFORMANCE OF INITIAL PROTOTYPE DMB USING UTAH BITUMINOUS COAL

PARAMETER	EXPERIMENTAL RANGE	OPERATING POINT FOR LOAD VARIATION TESTS	EFFECT
CORE	—	45° Open	—
INNER REGISTER	25-65° Open	45° Open	NO, STABILITY
OUTER REGISTER	35-90° Open	55° Open	FLAME SHAPE
INNER SLEEVE	—	100% Open	—
OUTER SLEEVE	25-100% Open	100% Open	AIR DISTRIBUTION
PRIMARY VELOCITY (Core nozzle Pos.)	0-3	3 in.	STABILITY
TERTIARY EXIT AREA (Port Diameter)	—	12 in.	—

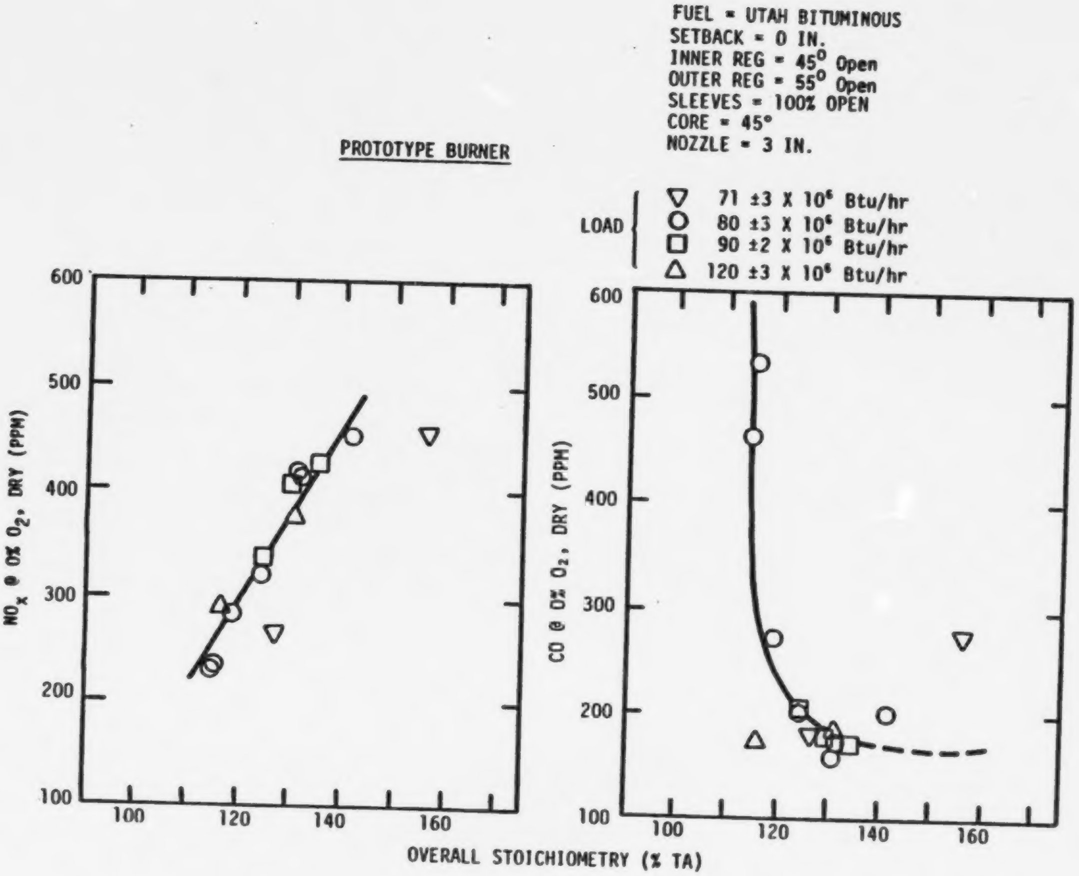


Figure 3-21. Effect of load on unstaged performance at the initial prototype DMB with setback = 0.

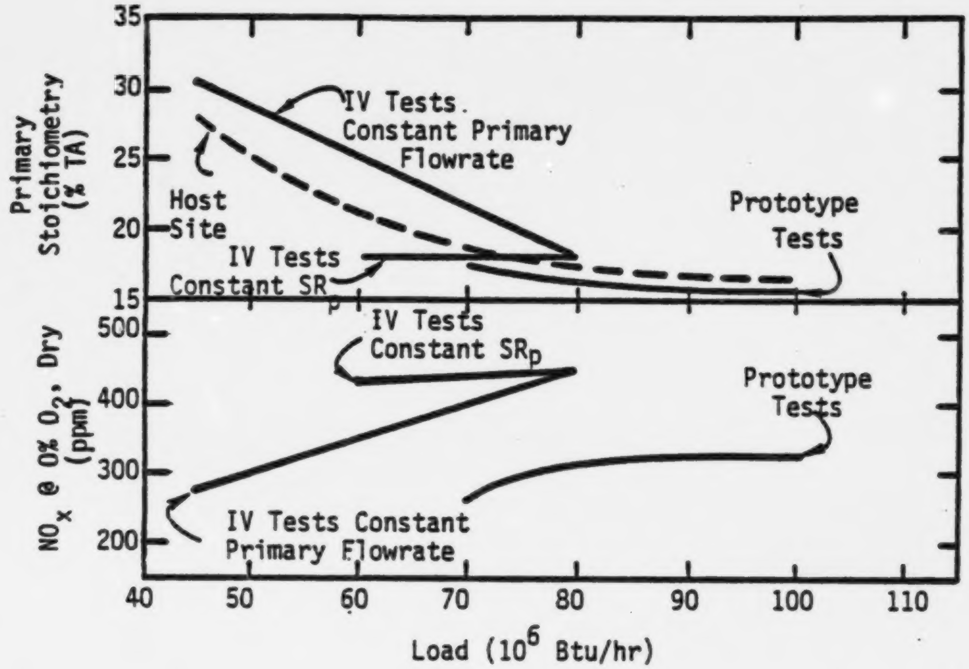


Figure 3-22. Comparison of the effect of load on intervane burner and initial prototype DMB unstaged performance.

for two reasons. First, changing the setback would move the coal introduction point further into the quarl, and second, earlier mixing of the primary and inner-secondary air streams should aid in flame stability.

The effect of changing the setback from 0.0 to 4.0 inches is illustrated in Figure 3-23. The reduced CO and increased NO_x emissions and the observation of more consistent burner performance were initial indications that the increased setback had improved stability. Note, however, that no noticeable change occurred in the flame standoff distance and that the flame shape was unaffected. Excess air variations at 4-inch setback, shown in Figure 3-24, verified that the knee of the CO curve was shifted to lower excess air. Hence, the operating point of 118-123 percent T.A. is sufficiently stable that mill and other perturbations do not force the burner into unstable or high CO operating conditions. Note that the CO levels are lower for the initial DMB than for the Intervane Burner at similar conditions. Also, unstaged NO_x emissions are lower at low excess air levels for the prototype. This is attributed to the larger throat diameter on the prototype resulting in lower velocity and slower mixing. Smoke levels were comparable for both burners.

However, it should be noted that this initial prototype DMB geometrical configuration was not optimized. Since this design was based on Foster Wheeler's commercial hardware, adapted to meet DMB velocity and flow criteria, further geometrical changes were necessary to obtain optimum NO and CO performance with acceptable stability. Among the differences between this prototype and EER's previous experimental DMBs are:

Initial Prototype DMB	Experimental DMBs
Registers for swirl control	Swirl Vanes
Annular coal nozzle with tangential inlet	Axial coal nozzle with or without swirl
Open coal nozzle outlet with adjustable velocity feature	Impeller/swirler at nozzle outlet, fixed velocity
Medium quarl depth	Long quarl depth

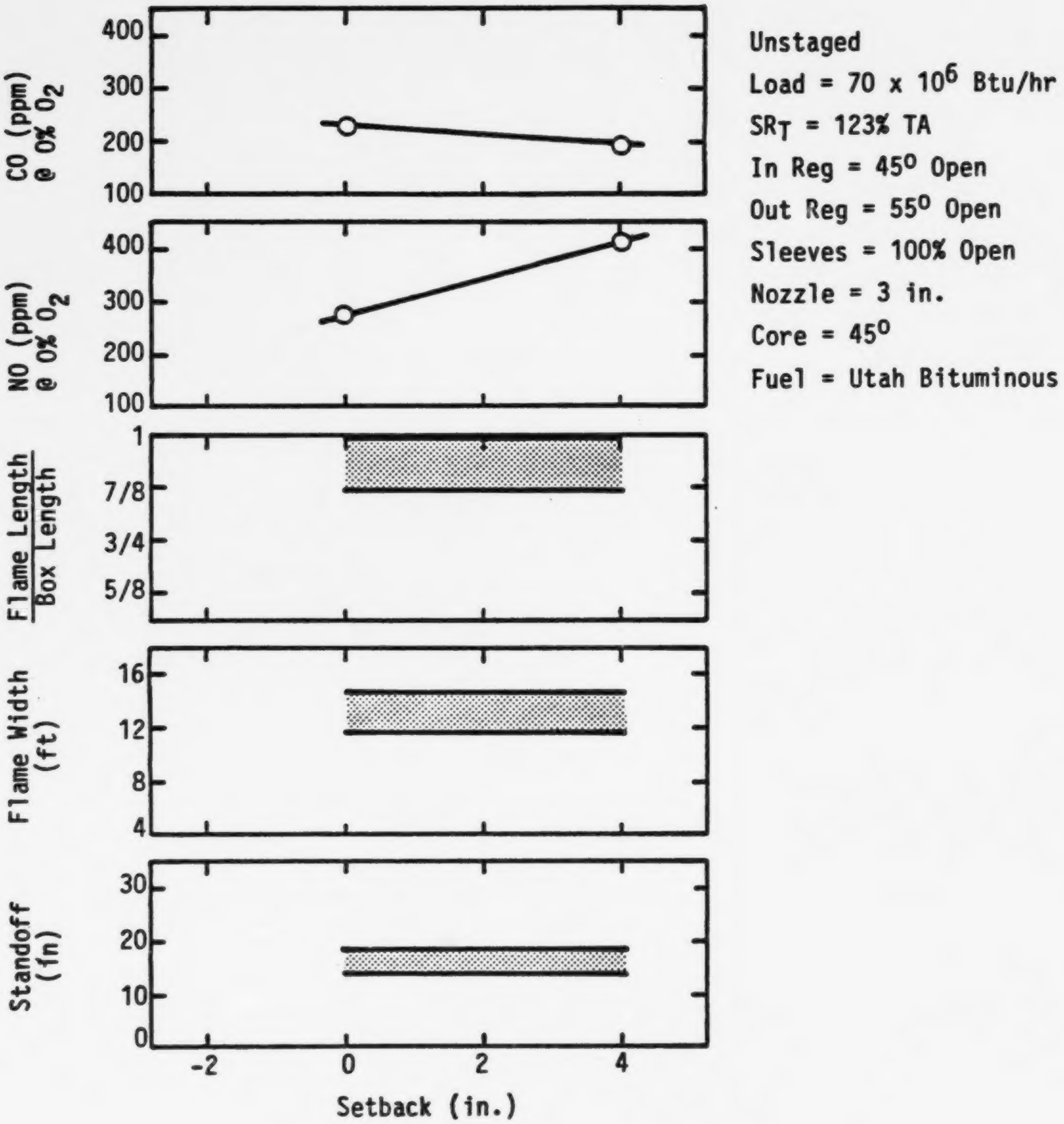


Figure 3-23. Effect of nozzle setback on unstaged performance of initial prototype DMB.

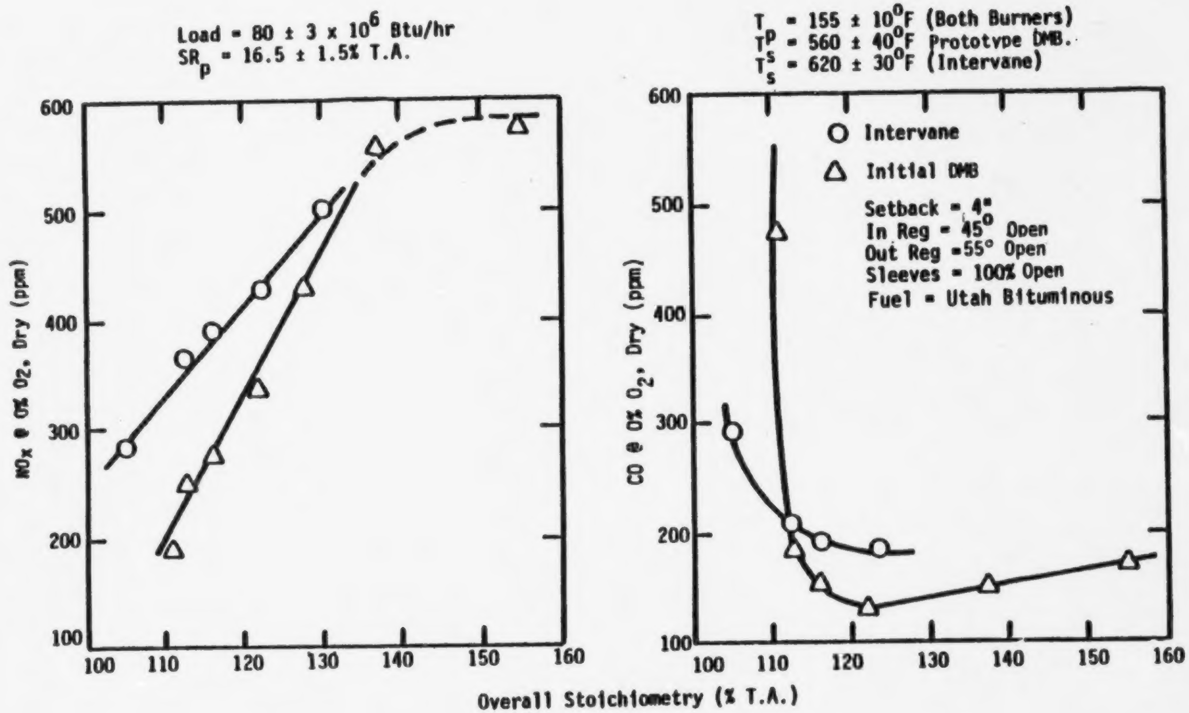


Figure 3-24. Effect of overall stoichiometry at full load on unstaged performance of Intervane burner and initial prototype DMB.

These differences can result in NO and CO performance which are also different. The prototype results were obtained with an initial geometry which is likely to be non-optimum.

3.3.3 Staged Tests of the Initial Prototype DMB in the Old and New LWS

A limited test series was conducted in the original LWS with the initial prototype DMB operating staged to obtain an approximate indication of its potential for low NO_x emissions. These tests were preliminary and were halted when the LWS furnace walls deteriorated. Consequently, no attempt was made to optimize burner adjustments and the burner was not operated at the design point. The results in Figure 3-25 show the same decrease in NO_x emissions as burner zone stoichiometry decreases as that observed in tests of other DMB designs. Extrapolation to the DMB design point, overall stoichiometry 118 percent theoretical air and burner zone stoichiometry 70 percent theoretical air, results in approximately 100 ppm NO_x. CO emissions increased to unacceptable levels as burner zone stoichiometry decreased. This is probably due to the cold LWS furnace as well as non-optimum burner configuration and adjustment. Optimization of burner adjustments and of burner geometry should result in the characteristic knee observed in the development DMB tests.

The LWS was rebuilt and additional tests with this initial DMB were conducted. The design of the new LWS and comparisons with the old LWS are discussed in Appendix A. The most significant difference in furnace designs is the thermal environment. The new LWS was partially lined with refractory to increase the heat release per unit cooled surface area to the range of field operating boilers. The objectives of these tests in the New LWS were to compare the prototype burner's performance in the new LWS with the previous test data in the Old LWS (to evaluate the effects of the change in thermal environment) and to further evaluate prototype burner performance under staged conditions. The prototype burner was installed in the new LWS and tested at the same conditions and burner settings as the previous tests, except for the nozzle, which was set at zero.

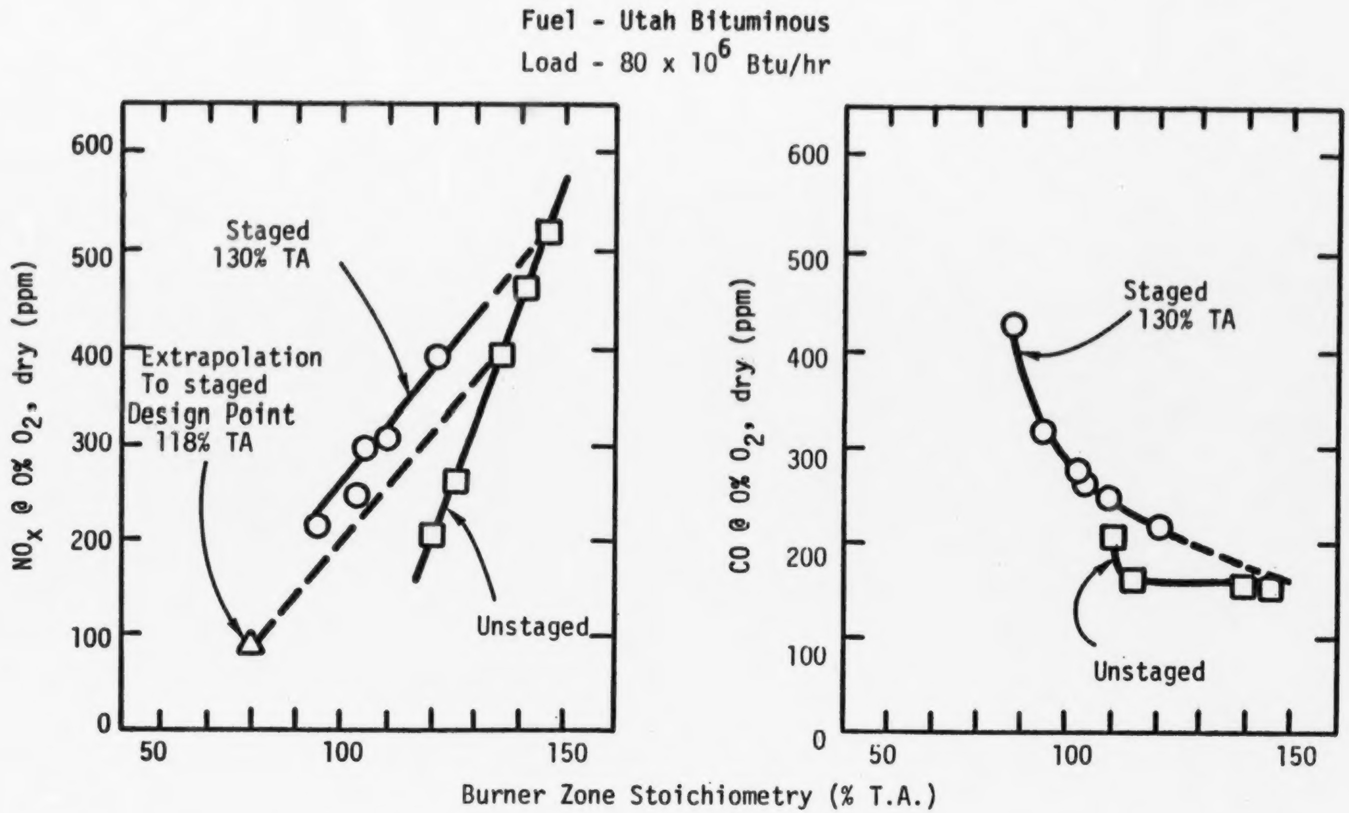


Figure 3-25. Initial prototype DRB staged performance in the original LWS.

The burner was tested unstaged with only leakage airflow (about 9-10 percent theoretical air) passing through the tertiary ports. The flame shape was comparable to the shape in the old LWS under similar test conditions. The standoff distance was approximately 8-12 inches and the flame length was about 12 feet. Flame stability was unaffected by load over the range 40-100 x 10^6 Btu/hr. The actual stability range may be greater since no attempt was made to operate outside this range. The unstaged NO_x and CO emissions at full load are shown in Figure 3-26. The NO_x emissions were slightly lower than the trend of the data in the original LWS. Considering data scatter and experimental error, there was no change in NO_x emissions. However, CO emissions were much lower in the new LWS. At the unstaged design point (118 percent theoretical air) CO was about 75 ppm compared with 150 ppm in the old LWS.

The initial DMB was also tested staged. The NO_x and CO emissions are shown in Figure 3-27. Note that the overall stoichiometry was approximately at the design point and lower than the stoichiometry for the tests in the old LWS. Extrapolating the old LWS data to the design point overall stoichiometry yields the dotted line in Figure 3-27. Thus the staged NO_x emissions in the old and new LWS were comparable. As with the unstaged data, the CO emissions from the staged tests were considerably lower in the new LWS. The CO emissions were within the same range as the unstaged data (less than 100 ppm) which is comparable to field data from commercial burners. At the lowest burner zone stoichiometry CO was slightly higher. This condition (burner zone stoichiometry 85 percent theoretical air) was the stability limit. At lower burner zone stoichiometry the flame lifted off the burner and CO emissions increased. Alternate burner settings were tested in an attempt to achieve stable operations at lower burner zone stoichiometry. Increasing the swirl had a negligible effect on emissions and stability. Retracting the nozzle (decreasing primary velocity) slightly reduced CO emissions and appeared to increase flame stability.

The stability limit for the prototype burner (85 percent theoretical air) is considerably higher than for the development DMBs (less than 50-70 percent theoretical air). This maybe due to the differences in nozzle and

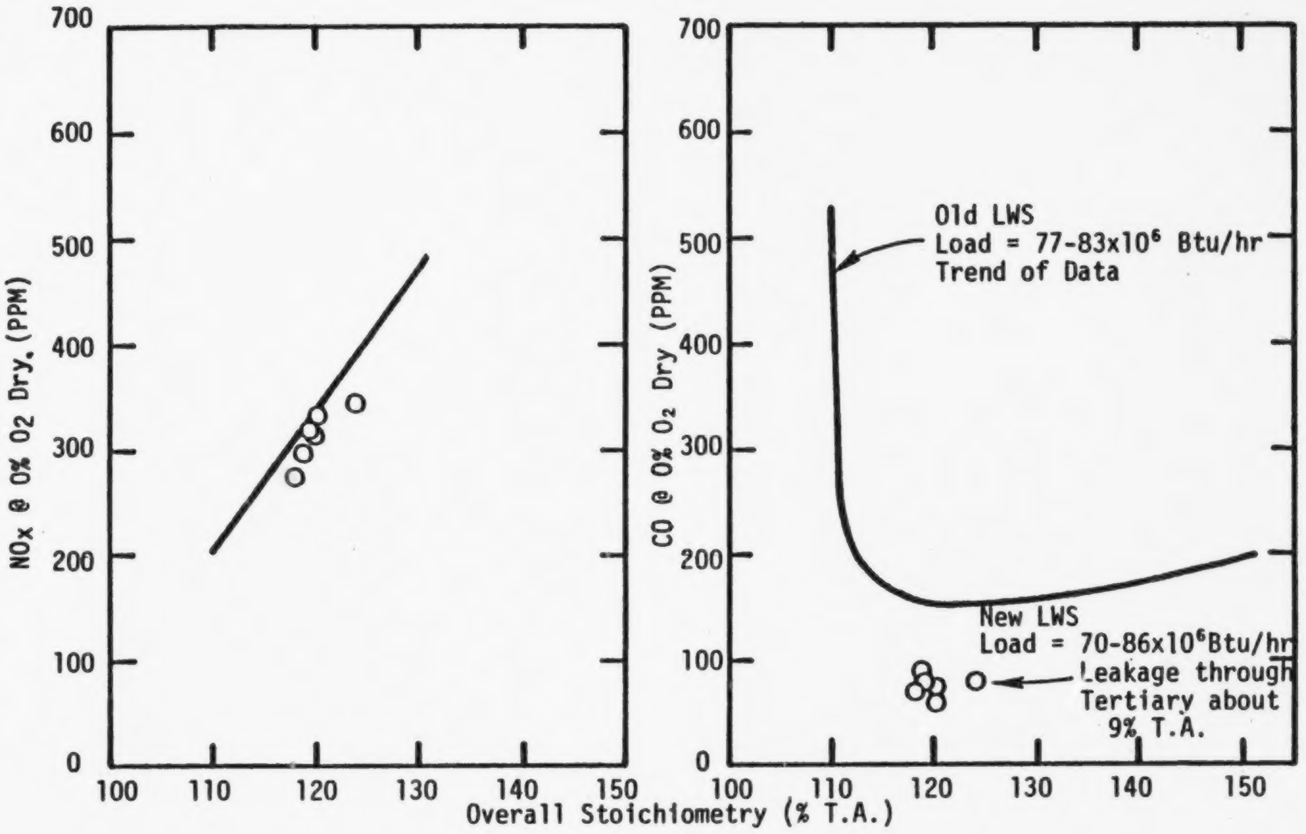


Figure 3-26. Comparison of unstaged performance of the initial DMB in old and new LWS firing Utah Bituminous coal.

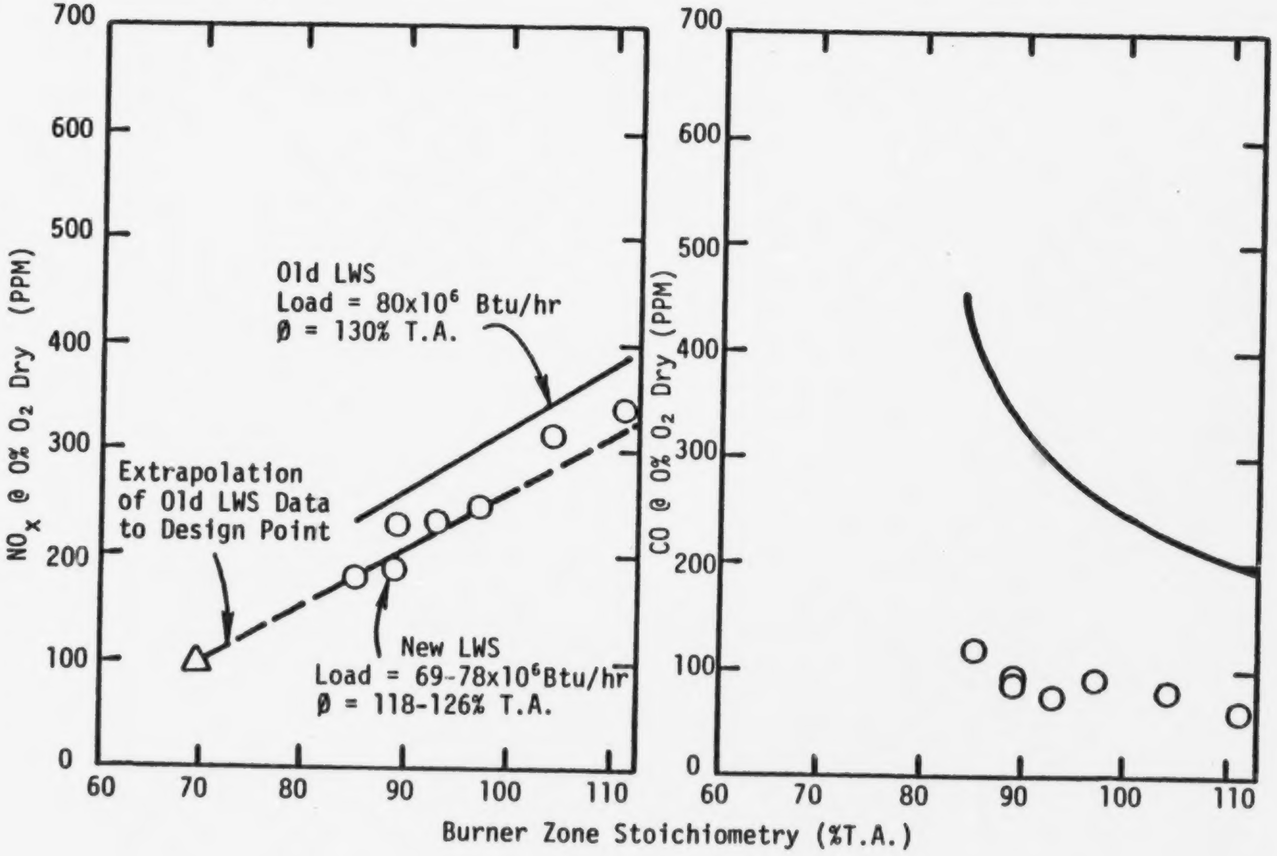


Figure 3-27. Comparison of staged performance of the initial prototype DMB in old and new LWS firing Utah bituminous coal.

exit designs. The prototype burner nozzle is annular, while axial nozzles with spreaders were used on the development DMBs. The prototype burner exit lengths were considerably shorter than the development DMBs due to limited windbox depth at the initial demonstration site.

In summary, the prototype burner performance in the new LWS was similar to the previous tests in the old LWS, except for the CO emissions which were much lower in the new LWS and comparable to field levels. This confirms that the high CO emissions measured with pre-NSPS burners and DMBs in the old LWS were related to furnace, rather than burner, design. There was essentially no increase in NO_x emissions even though the new LWS furnace is considerably "hotter" than the old design.

3.4 DMB With Foster Wheeler Parameters

The inability of the initial prototype DMB to operate at the design point, burner zone stoichiometry of 70 percent theoretical air necessitated modification and further testing of the prototype DMB. Stability limits were observed during some of the testing that developed the EPA DMB design criteria and performance was improved by adjusting the nozzle and exit geometry. The original test plan called for the iterative development and modification of burner geometry to optimize the performance of the prototype DMB for low emissions, high efficiency, and acceptable operating range. However, this would have delayed the installation of DMBs at WIPCO by about one year due to the boiler outage schedule. The alternative was to incorporate a burner configuration known to be stable under staged operating conditions and to confirm burner performance in the new LWS while preparations were being made for the field installation. The Foster Wheeler Controlled Flow Burner had been operated in Japan with burner zone stoichiometries comparable to the DMB but using overfire air ports instead of tertiary air ports which surround the burner exit. Thus it was decided to incorporate the Foster Wheeler geometry into the prototype DMB.

The second prototype DMB with Foster Wheeler parameters was designed by modifying the burner geometry to match the geometry of the Foster Wheeler

Controlled Flow Burner. This included changes to the nozzle, cast refractory exit and flow divider between the inner and outer secondary air passages. The parallel register arrangement of the initial prototype burner was retained. It should be noted that the Foster Wheeler Controlled Flow Burner has a series register configuration with a single perforated plate and air hood assembly.

The Controlled Flow geometry is representative of Foster Wheeler's advanced burner designs and is considered proprietary by Foster Wheeler. Utilization of this geometry to expedite the field demonstration required negotiation of a confidentiality agreement between EER and Foster Wheeler. The agreement prevents disclosure of the Foster Wheeler exit geometry, optimizing parameters and test data for burner zone stoichiometries greater than 85 percent TA.

The modified DMB with Foster Wheeler parameters was evaluated in the four test series listed in Table 3-7. Included in the tests were a brief series conducted unstaged to verify operation of the burners should the tertiary air system at the field unit fail. Staged performance was optimized in the new LWS and evaluated with three different fuels. Finally, the modified DMB was tested in the EER Medium Tunnel (MT) to evaluate effects of thermal environment and confinement. These tests focused on NO_x emissions and are discussed in the following four subsections. Subsection 3.4.5 compares the performance measures in the LWS to the WILCO retrofit requirement. This test series also included sorbent injection for SO_2 control. These and similar tests with the final prototype burner are discussed in Section 3.6.

3.4.1 Unstaged Performance Verification

The initial tests of the DMB with Foster Wheeler parameters were conducted in the new LWS under unstaged conditions with Indiana coal. The objective was to verify that the burner could operate as a conventional burner with the tertiary air ports closed. This would ensure that the burner could be ignited in the conventional manner and adjusted to staged operation

TABLE 3-7. TEST APPROACH FOR DMB WITH FW PARAMETERS

Test Series	Staging	Fuel	Furnace
1. Unstaged Performance Verification	Unstaged	Indiana	New LWS
2. Staged Performance Optimization	Staged	Indiana	New LWS
3. Fuel Effects	Staged	Utah, Illinois	New LWS
4. Furnace Effects	Staged	Utah, Indiana	MT

for low NO_x emissions. Also, if problems with the tertiary air ports or control system occur, the burner could be operated with the ports closed without need for immediate repairs requiring an outage. The burner was tested in the LWS over the WIPCO load and excess air range. The flame was stable and could be ignited with the commercial Forney oil-fired ignition system. The flame scanner gave reliable signals for the pilot and main flames. The flame was bright with an overall length of approximately 4.0 m (13 ft). This is considerably shorter than the WIPCO furnace thus avoiding rear wall flame impingement. A more detailed analysis of unstaged performance is included in Appendix A.

3.4.2 Staged Performance Optimization

Following the unstaged performance tests, the DMB with Foster Wheeler parameters was tested under staged conditions in the new LWS with Indiana coal. The objective was to identify the burner settings which gave an optimum balance between flame stability, combustion efficiency and emissions over the host boiler operating range. The criteria used to establish the optimum operating point included the following:

1. Adequate flame stability at the design operating point: burner zone stoichiometry 70 percent T.A. and overall stoichiometry 120 percent T.A.
2. Flame stability insensitive to minor burner adjustments.
3. Flame shape compatible with WIPCO furnace.
4. High combustion efficiency as indicated by CO emissions and carbon content of the particulate samples.
5. Low burner pressure drop.
6. Turndown comparable to the Intervane Burner at WIPCO.
7. Low NO_x emissions.

The following burner settings gave optimum results in these new LWS tests:

- Inner Nozzle Cone Position = 0.0 in.
- Inner Register = 15° open

- Outer Register = 15° open
- Core Air Valve = 45° closed
- Secondary Air Sleeves = 100 percent open

These settings were used for all subsequent tests.

At the optimum burner settings, the flame was stable over a wide range of burner zone stoichiometries from unstaged conditions down to 64 percent theoretical air. As the burner zone stoichiometry was decreased, the flame length increased from 13 ft for unstaged conditions to about 19 ft at the design point. These flame lengths are estimates based on direct observation and color video. To confirm the flame length, the composition of the furnace gases was measured near the rear wall. High CO levels and/or low O_2 levels near the rear wall would indicate flame impingement and vice versa. The results are summarized below.

Location	O_2 (%)	CO @ 0% O_2 (ppm)
Furnace, 4 in from rear wall	3.4	95
Furnace, 18 in from rear wall	3.2	165
Furnace, 30 in from rear wall	3.0	1400
Furnace, nose	5.3	58
Exhaust	4.5	57

These data indicate that an oxidizing environment is present on the rear wall. As the sampling location was moved further into the furnace, the O_2 concentration decreased and the CO concentration increased. The 19 ft flame length observed visually corresponds to 24 in from the rear wall. This is approximately the location of a considerable increase in the CO concentration.

The NO_x and CO emissions at full-load are shown in Figure 3-28. These results are similar to those obtained with the development DMBs and the initial prototype DMB. For fixed overall stoichiometry, NO_x emissions decreased approximately linearly as the burner stoichiometry decreased. Thus

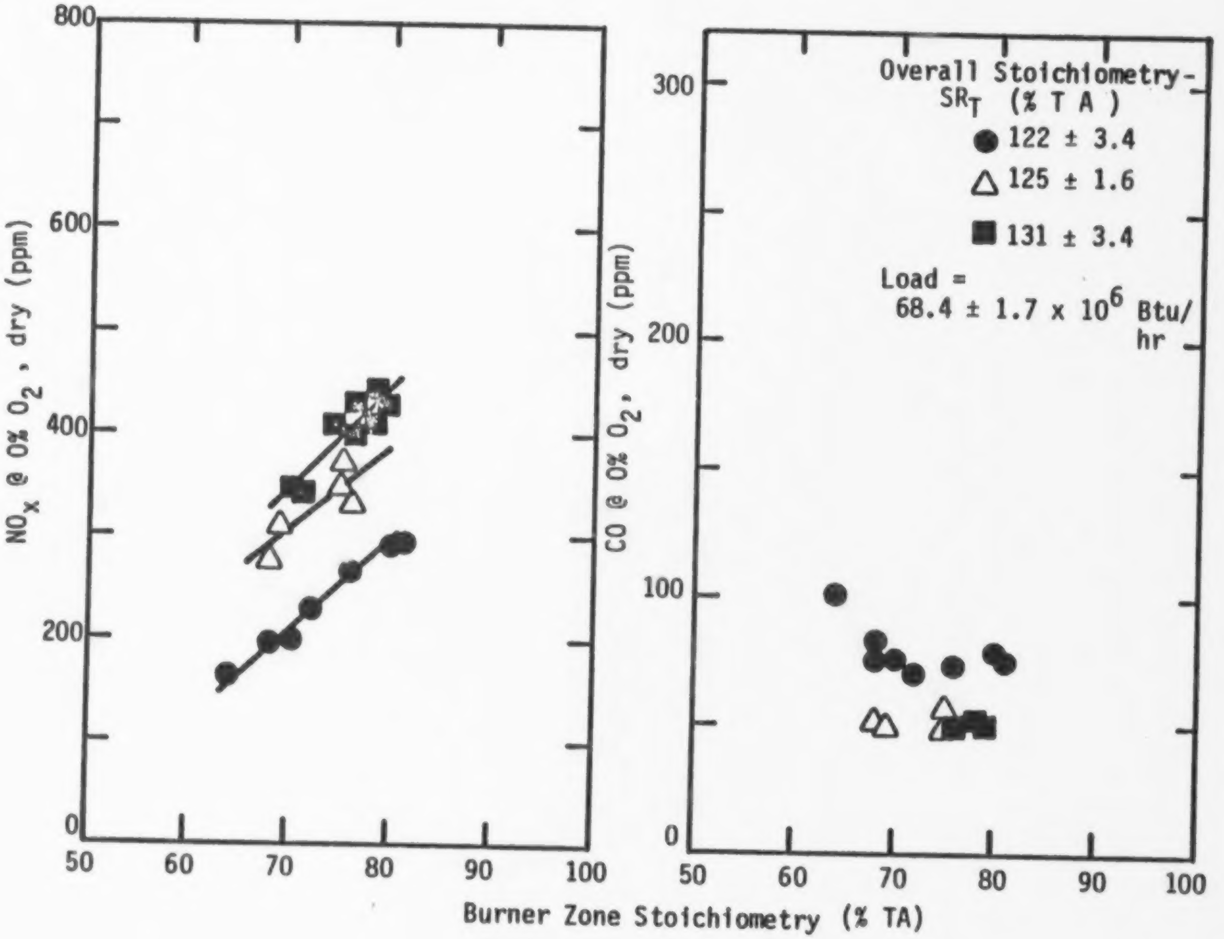


Figure 3-28. Performance of prototype DMB with Foster Wheeler parameters at optimum configuration in new LWS firing Indiana 2 coal.

it is desirable to operate at the lowest burner zone stoichiometry where flame stability and combustion efficiency are acceptable. As burner zone stoichiometry is decreased, CO emissions remain constant initially and then increase. Further decreases in burner zone stoichiometry result in flame instability with a flame stability limit of about 64 percent T.A. At the design point (70 percent T..A.) NO_x emissions are 200 ppm, which corresponds to 96 ng/J (0.22 lb/10^6 /Btu), and CO emissions are about 70 ppm which is in the range of typical commercial burners, less than 100 ppm. NO_x emissions are also sensitive to excess air with a slope of about 15 ppm/percent T.A. CO emissions and flame characteristics remained constant over the range shown.

Carbon loss was measured by collecting grab samples of fly ash in the new LWS exhaust and measuring the carbon content of the samples. Carbon loss depends on burner performance in providing adequate fuel/air mixing, the furnace thermal environment particularly in the post flame region and the reactivity of the coal char. The test facilities used to evaluate prototype burner performance were designed primarily to simulate the thermal environment in the flame zone which impacts NO_x emissions. The thermal environment downstream of the flame zone was cooler than in full scale boilers and this should tend to increase carbon loss. Thus, in evaluating carbon loss data for the prototype burner test, the trends of the data are more important than the absolute values. Figure 3-29 shows carbon content of the fly ash measured over a range of burner zone and overall stoichiometries in the new LWS tests at optimum settings with three fuels. In the previous discussion it was assumed implicitly that the trends of CO emissions were related to the trends of carbon loss. These data confirm this approximately. Also, carbon loss tends to increase as NO_x emissions decrease. The effect of coal type is within the data scatter and thus undiscernible.

Other measurements at optimum burner settings included hydrocarbon emissions and N_2O. Hydrocarbon emissions were lower than the detectibility limit (1.0 ppm) for the two conditions tested. N_2O emissions were 39 and 42 ppm for two tests.

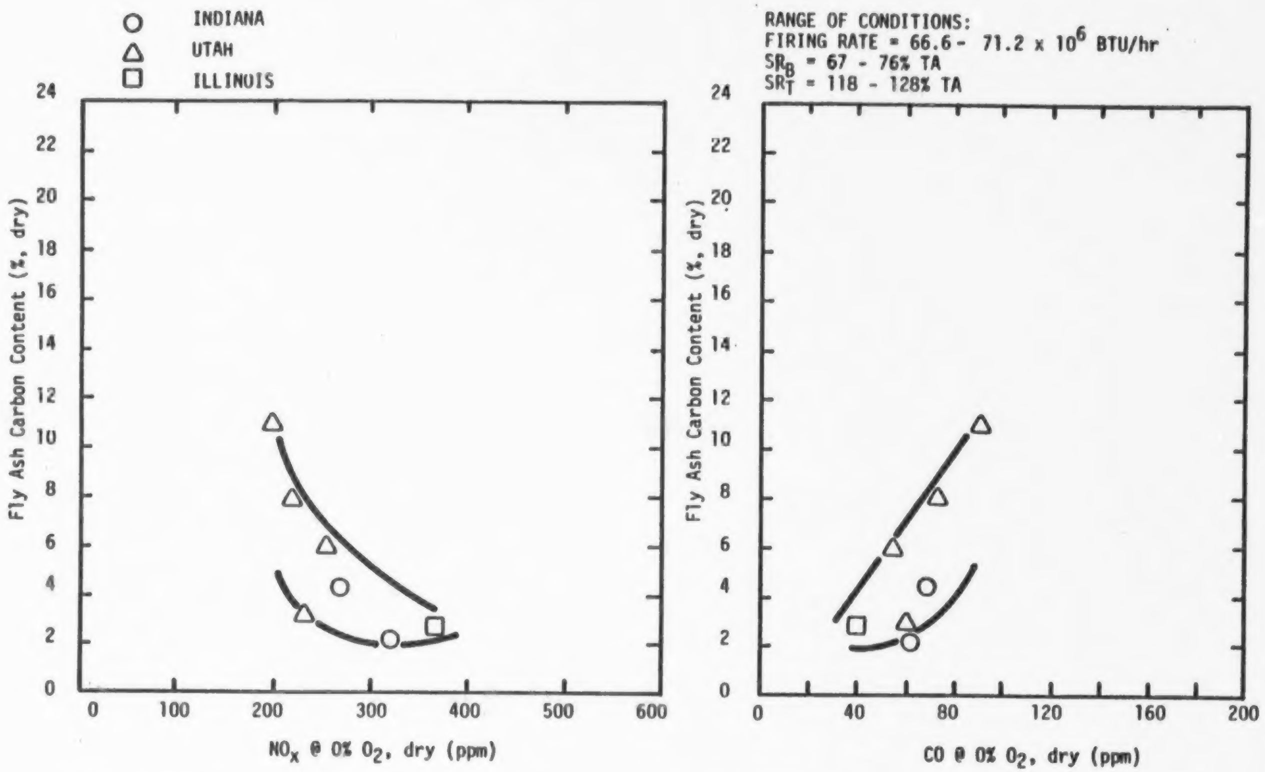


Figure 3-29. Range of fly ash carbon content for DMB with FW parameters at optimum burner configuration in new LWS.

Burner performance was evaluated over the load range with fixed burner settings. The new LWS test facility has a CE Raymond bowl mill which requires constant primary air flow rate for proper coal pulverization. Figure 3-30 illustrates the changes in air flow rates and stoichiometries that occur over the load range with fixed burner settings. The primary stoichiometry increases as load is reduced. This differs somewhat from the air flow characteristics of the Foster Wheeler MB mills at the WIPCO boiler where the primary air flow rate decreases as load is reduced, eventually leveling off to a constant flow rate for low loads. This difference between the characteristics of the pulverizers should not affect burner performance significantly over the conditions tested. Assuming constant overall stoichiometry, the total air flow rate is proportional to the load. Thus, the windbox air flow rate decreases as load is decreased. The distribution of windbox air flow between the registers, core and tertiary air ports is independent of the total air flow rate but can be controlled by varying the burner settings. The net effect is a slight increase in burner zone stoichiometry and a considerable decrease in air flow through the registers as the load is decreased. This can cause flame instability at low load. The solution is to increase the air flow rate through the register by increasing the overall stoichiometry or closing the tertiary air ports. The approach used in the prototype burner tests was to increase overall stoichiometry.

Figure 3-31 shows the performance of DMB with FW parameters over the load range. At full-load 70 x 10^6 Btu/hr, the burner was set-up for an overall stoichiometry of 122 percent T.A. and a burner zone stoichiometry of 72 percent T.A. Load was decreased, maintaining the overall stoichiometry constant down to 48 x 10^6 Btu/hr. Further decreases in load resulted in a pronounced increase in CO emissions and flame instability. To restore flame stability at lower load, the overall stoichiometry was increased to 132 percent theoretical air. This increased NO_x emissions but allowed stable operation down to 37 x 10^6 Btu/hr which corresponds to a turndown of about 50 percent from full-load.

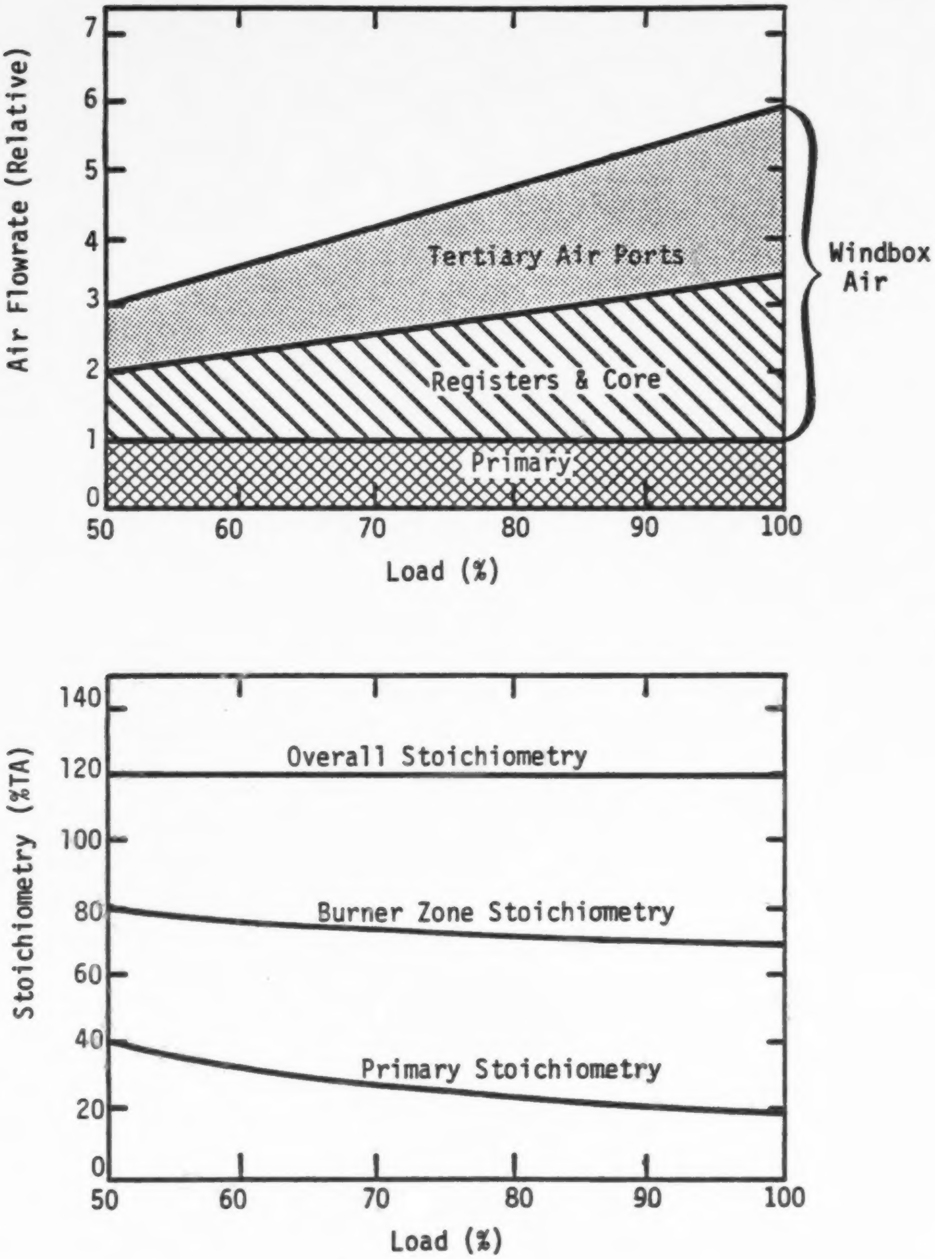
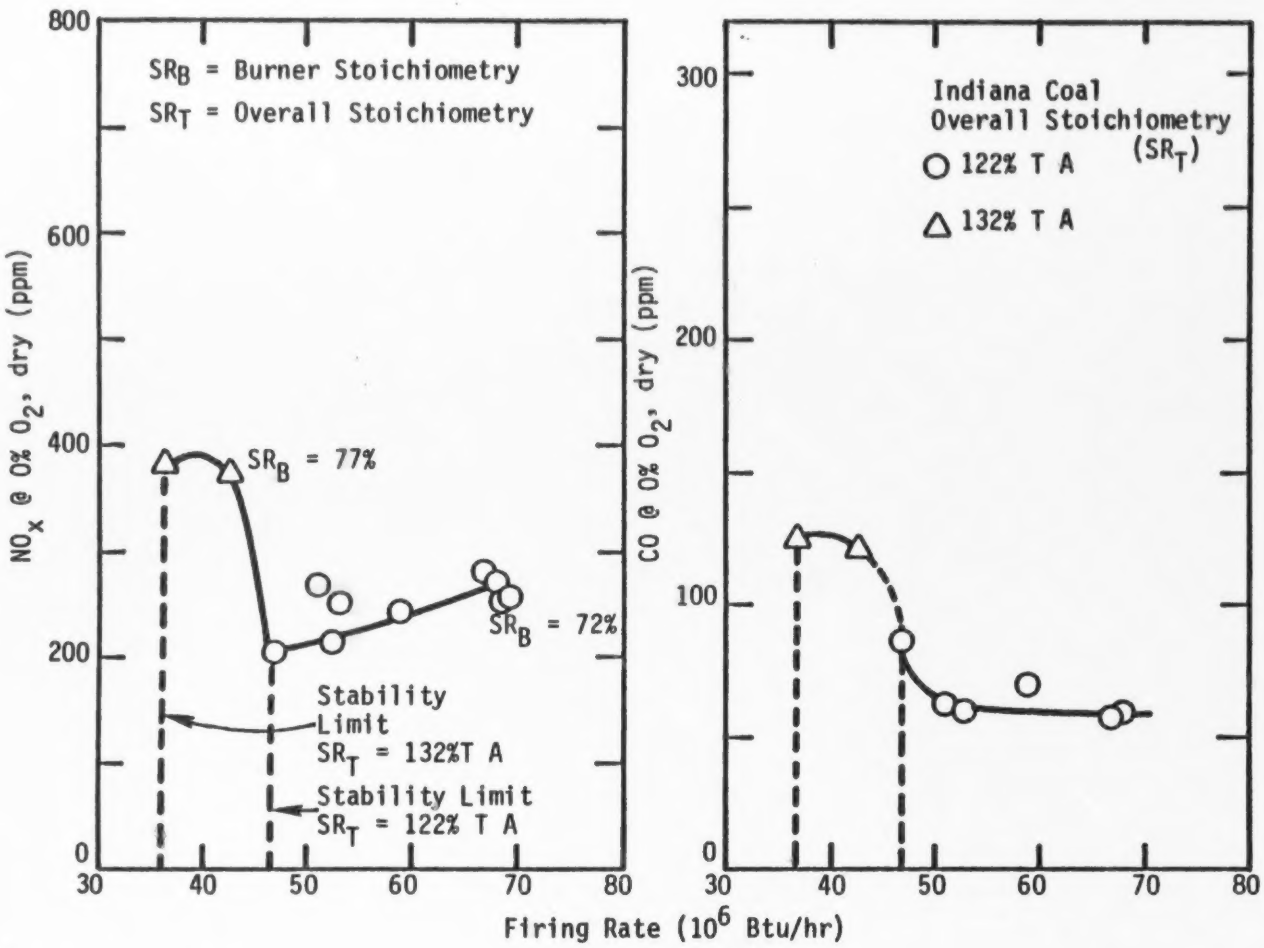


Figure 3-30. Air flowrates and stoichiometries over load range.



NOTE:
1.0 Btu/hr = 0.293 W

Figure 3-31. Turndown range of DMB with FW parameters in the new LWS.

3.4.3 Fuel Effects in New LWS

The preceding tests were conducted with the burner design fuel, Indiana 2 coal. To evaluate the effect of fuel composition, two additional high volatile bituminous coals were tested, Utah 2 and Illinois coals. The compositions of these coals are listed in Appendix C. The tests were conducted at full load over a range of burner zone stoichiometries. NO_x and CO emissions from all these fuels are compared in Figure 3-32. Flame shape, stability and CO emissions for all the coals were comparable. NO_x emissions from the Utah and Indiana coals were almost identical. However, the NO_x emissions from the Illinois coal were about 100 ppm higher. The reasons for this increase are not clear. The test conditions for all three fuels were similar and the fuel compositions are only slightly different. In comparison to the Indiana and Utah coals, the Illinois coal was higher sulfur, lower nitrogen, lower heating value and lower volatility.

3.4.4 Furnace Effects

Following the new LWS tests, the DMB with FW parameters was fired in the MT to evaluate the effects of furnace confinement. In comparison with the new LWS, the MT is cylindrical as opposed to rectangular and much smaller. Also, it has smaller cooled surface area in the burner zone. These differences were expected to influence the flame characteristics and NO_x emissions. It was planned to fire the burner in the MT at the nominal capacity of 70×10^6 Btu/hr. However, this firing rate could not be achieved due to the volume of the flame which exceeded the MT furnace volume. Figure 3-33 compares the flame characteristics in the new LWS and MT. In the new LWS, the flame length was about 19 ft which is 3 ft shorter than the furnace depth. In the MT, the flame was constrained by the furnace and extended into the exhaust duct. To avoid overheating of the MT furnace components, the tests were conducted at about 50×10^6 Btu/hr. At this firing rate in the MT, the heat release per cooled surface area was comparable to full-load firing in the new LWS. However, the net heat extraction was greater in the new LWS. Furnace exit temperature measurements with an aspirating thermocouple were up to 500°F higher in the MT. Gas temperature measurements

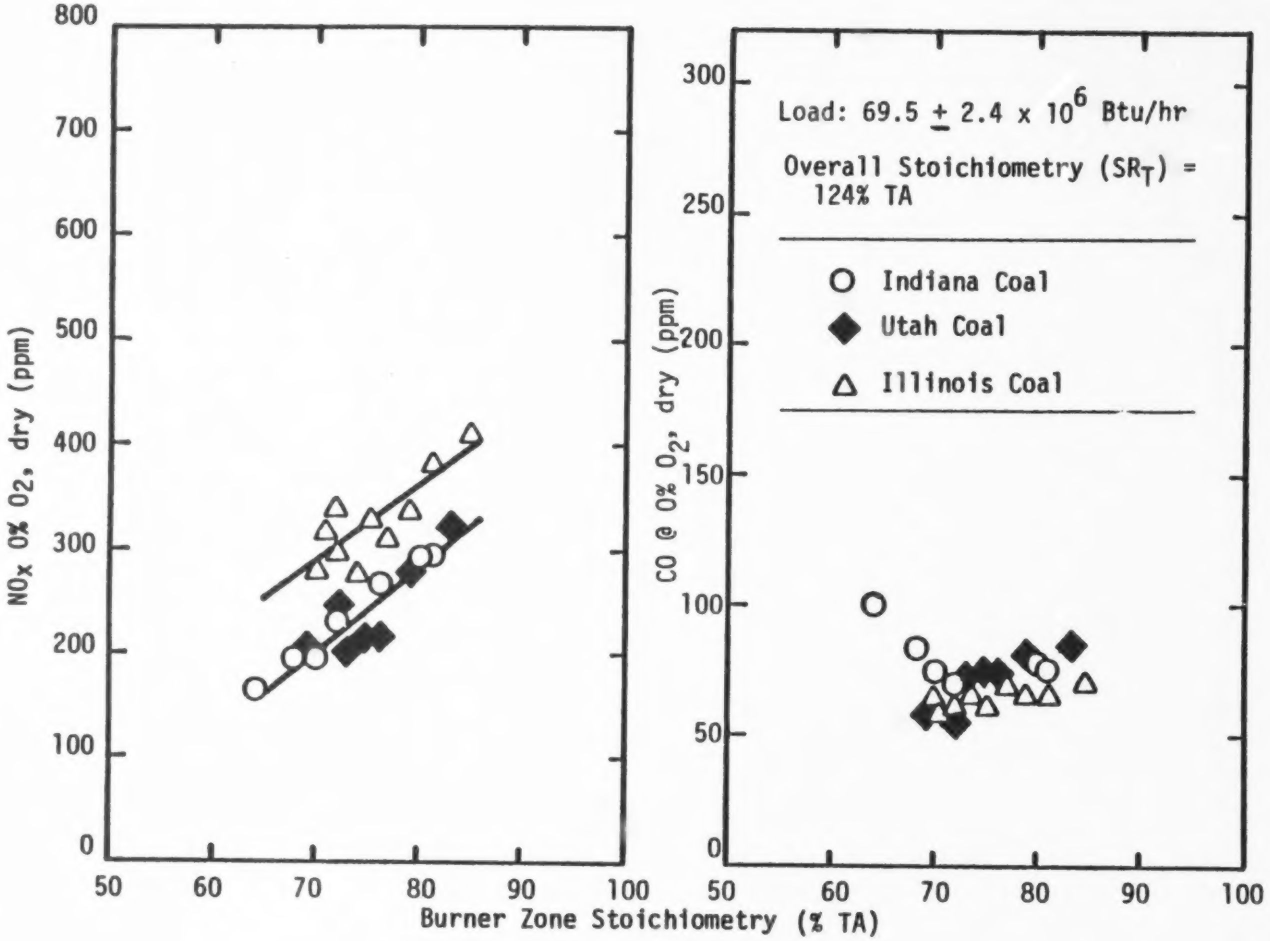
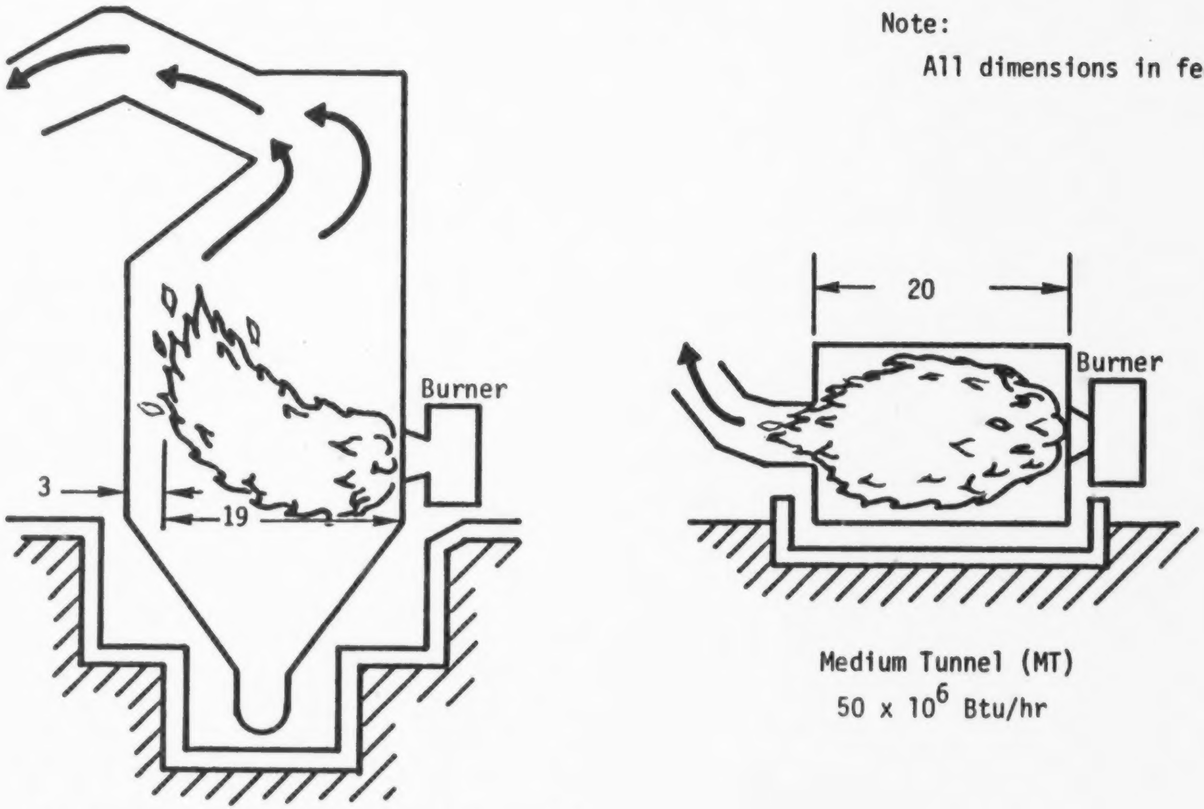


Figure 3-32. Effect of fuel composition on DMB with FW parameters performance in new LWS.



Note:
All dimensions in feet.

New Large Watertube Simulator (New LWS)
70×10^6 Btu/hr

Medium Tunnel (MT)
50×10^6 Btu/hr

Figure 3-33. Containment of the flame produced by the DMB with FW parameters in the new LWS and MT research furnaces.

at the sampling location in the exhaust duct were about 200°F higher in the MT.

NO_x and CO emissions measured in the new LWS and MT with Indiana coal are compared in Figure 3-34. In the MT, NO_x emissions are higher and CO emissions are lower than in the new LWS. Figure 3-35 shows similar trends for the Utah coal. It should be noted that the new LWS results shown in Figures 3-34 and 3-35 are at higher load than the MT results. Based on the load data in Figure 3-31, the NO_x levels in the new LWS at the MT firing rate would be about 40 ppm lower. Thus, comparing the MT and LWS at the same firing rate results in differences somewhat greater than those plotted Figures 3-34 and 3-35.

The differences between the FW prototype DMB performance in the new LWS and MT may be due to two factors: thermal environment and furnace confinement. The effects of thermal environment on NO_x emissions from the initial prototype DMB were evaluated by testing in the old and new LWS. The furnace geometries for these furnace are almost identical. The primary difference is thermal insulation in the new LWS which reduced the cooled surface area by a factor of about two. NO_x emissions from the initial prototype DMB in the old and new LWS were comparable. This indicates that NO_x emissions were unaffected by thermal environment over the range investigated. Of course, as furnace cooling is reduced further, NO_x emissions would be expected to increase due to thermal NO_x formation.

The smaller size of the MT narrowed and elongated the flame and this may have altered the mixing of the tertiary air. Since the basis of the low NO_x emissions of the DMB is delayed mixing of the tertiary air, this may have increased NO_x emissions.

3.4.5 Application of the Prototype DMB With FW Parameters to WIPCO

One key objective of the prototype burner tests was to verify that all aspects of the burner performance meet the host boiler requirements. Table 3-8 compares the requirements of the WIPCO unit with the performance of the

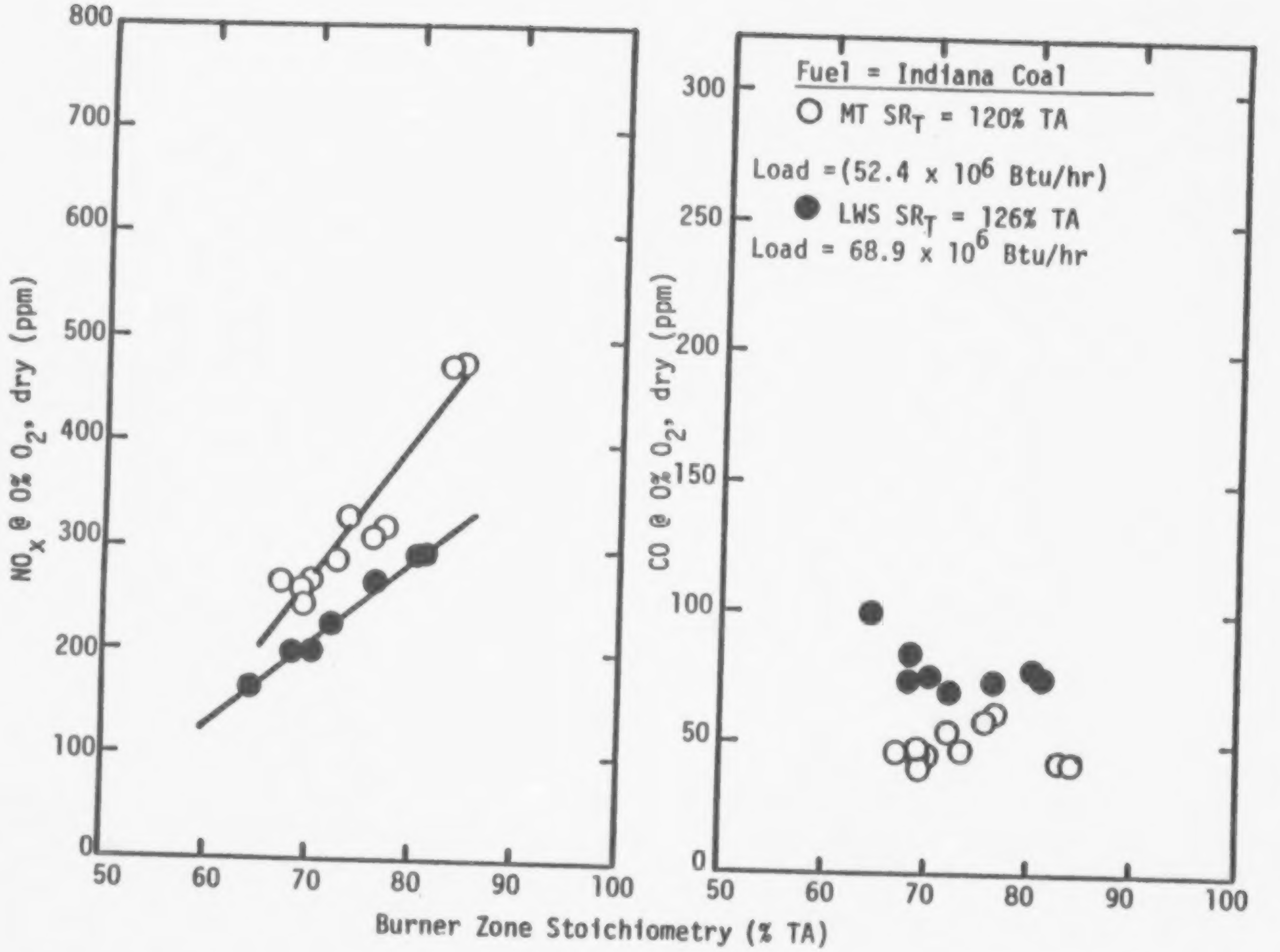


Figure 3-34. Comparison of DMB with FW parameters performance in the new LWS and MT with Indiana coal.

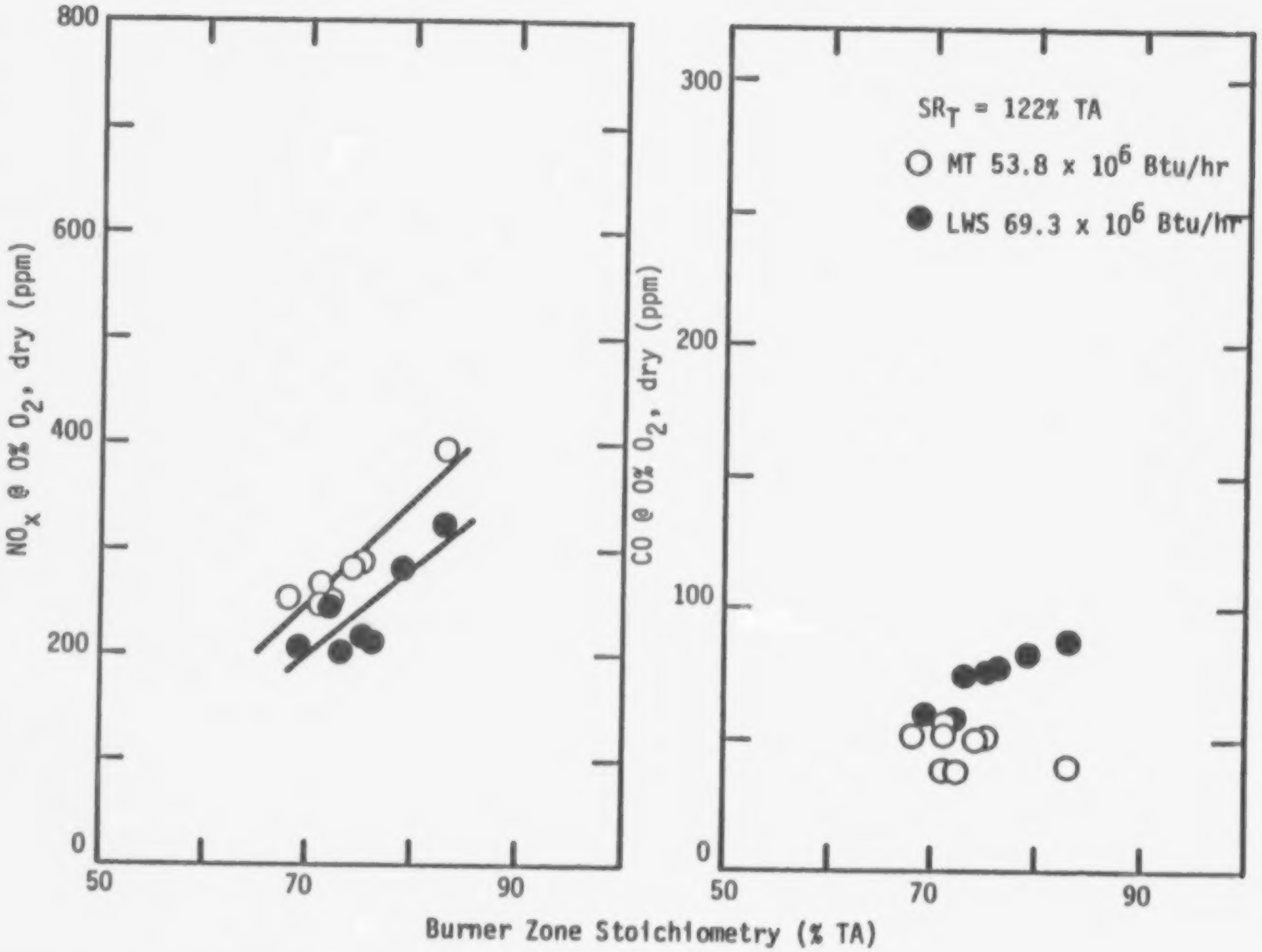


Figure 3-35. Comparison of DMB with FW parameters performance in the new LWS and MT with Utah coal.

TABLE 3-8. PERFORMANCE SUMMARY OF THE PROTOTYPE DMB WITH FW PARAMETERS

Parameter	Requirement	Demonstrated Performance
Flame Shape	Compatible with host furnace	Flame length:
Flame Stability	Stable over host load range; Insensitive to burner settings	Minimum load less than 50 percent MCR* Stability insensitive
Ignition	Compatible with commercial system	Confirmed
Flame Scanning	Compatible with commercial system	Confirmed
Pressure Drop	Less/equal to host burner	1.5 to 2.5 in H_2O
Efficiency	Equal/better than host burner	Carbon in ash = 2.3 11.0 percent
Tertiary Ports	Locations compatible with host furnace	Ports redesigned for Field Evaluation
Control System	Compatible with commercial standards	
NO_x	Program goal: 87 mg/J (0.2 lb/10^6 Btu)	0.22 lb/10^6 Btu at design point sensitive to excess air and burner zone stoichiometry Insensitive to load

* Maximum Continuous Rating

FW Prototype DMB in the new LWS. The new LWS furnace geometry is similar in shape to the WIPCO furnace. The flame length in the new LWS was 19 ft which is shorter than the WIPCO furnace depth, 20.6 ft. Thus, rear wall flame impingement should not be a problem at WIPCO. The flame was stable over the WIPCO load and excess air ranges and flame stability was not affected by small changes in burner settings or burner zone stoichiometry. The flame scanning and ignition system operation was compatible with commercial standards.

Windbox-to-furnace pressure drop with the secondary sleeves open full was in the range of 1.5 to 2.0 in H_2O. This is less than the 3.5 in pressure drop required by the original equipment Intervane Burner. This should reduce fan power requirements. However, if system imbalances occur the secondary sleeves may be closed to increase the pressure drop.

CO emissions and the carbon content of the fly ash were greater in the new LWS prototype burner test than the values measured during the WIPCO baseline test. However this is probably not significant since the thermal environment in the post flame regions of the test facilities are cooler than in the WIPCO furnace and this tends to increase CO emissions and carbon loss. However, carbon loss was found to increase as NO_x emissions decreased. This suggests that the minimum achievable NO_x emissions at WIPCO may be limited by carbon loss constraints. Also, it should be noted that the prototype burner was tested with a symmetric array of four tertiary air ports while the WIPCO DMB installation had an unsymmetric array of ports around each burner (see Section 4.0). Unsymmetric tertiary air port arrays tended to increase CO emissions (and potentially carbon loss) in the development DMB tests.

NO_x emissions with the design fuel (Indiana coal) were 0.22 lb/10^6 Btu at the optimum full load operating point. This is very close to the program goal of 0.2 lb/10^6 Btu. The differences between the prototype burner tests in the new LWS and the field operating DMBs at WIPCO were expected to affect NO_x emissions. These differences included the following:

Parameter	Prototype Tests in LWS	WIPCO DMB Field Evaluation
Number of Burners	1	4
Number of Tertiary Air Ports	4	13
Fuels	Primary	Varies
Furnace Depth (ft)	(22)	(20.6)
Thermal Environment, Q/A (Btu/hr-ft^2)	100,000	130,000

The precise effects of these differences could not be evaluated based on existing data. Minimum NO_x emissions for the DMBs operating at WIPCO were expected to be in the range of 0.2 - 0.3 lb/10^6 Btu/hr providing that the operating conditions tested in the research furnaces could be achieved.

3.5 Final Prototype DMB

The initial approach to the DMB design was to integrate the DMB design criteria, Foster Wheeler burner components and the requirements of the host boiler into a prototype DMB. This burner was to be tested in the LWS and its design adjusted to achieve the best balance of performance. The prototype burner was designed and constructed as planned and the optimization testing was begun. However, due to the need to rebuild the LWS test facility and the resulting schedule delay, it was decided to cut short the optimization testing and to incorporate the Foster Wheeler controlled flow burner design parameters since burners using these parameters had been successfully operated at burner zone stoichiometries in the DMB range but with overfire air ports. Subsequent tests in the new LWS confirmed flame stability and the installation of the DMBs at WIPCO proceeded using this burner design.

While this approach produced a more timely field demonstration, there were two limitations: (1) the Controlled Flow Burner Design parameters are proprietary to Foster Wheeler and (2) there is no reason to expect that the

Controlled Flow Burner Design parameters would necessarily be optimum for the DMB with tertiary air ports. Consequently, following the installation of the DMBs at WIPCO, the development of the DMB was resumed following the initial approach. This involved modifying the prototype DMB to match the DMB design criteria. This final prototype burner design was then tested extensively in the new LWS. The approach is illustrated in Figure 3-36.

The EPA DMB design parameters specify an exit length-to-throat diameter ratio of 1.0. This long exit configuration was first evaluated unstaged to define the operational limits of the burner. Staged optimization of the burner controls involved a parametric test matrix that included variation of register vane position, secondary air flow distribution via sleeve position, and primary velocity using the adjustable core nozzle position. Coal nozzle setback was varied to optimized the exit geometry of the DMB. Increased setback was expected to increase flame stability. Once the optimum configuration was defined, the performance was evaluated over typical boiler load and excess air ranges. Also, the potential SO_2 reduction by the injection of dry sorbent materials through burner passages was evaluated for the optimum configuration. Following the tests with the long exit, A short exit design was tested and optimized following procedures similar to the long exit design, utilizing the previous results to expedite testing. The tertiary air velocity was varied during the short exit tests by decreasing the size of the ports. The results from tests of other DMBs suggest that high tertiary air velocities tend to decrease flame length at the expense of slightly higher NO_x emissions. However the smaller ports associated with higher velocities would be more practical in terms of field installations. Again, a detailed evaluation was conducted for the optimum short exit DMB design.

The design of the final prototype DMB is presented in the following subsection. The results of the unstaged and staged tests of the long exit configuration are presented in subsections 3.5.2 and 3.5.3 respectively. Results of the short exit configuration tests are discussed in subsection 3.5.4, and the effects of parameters that may need to be compromised in field

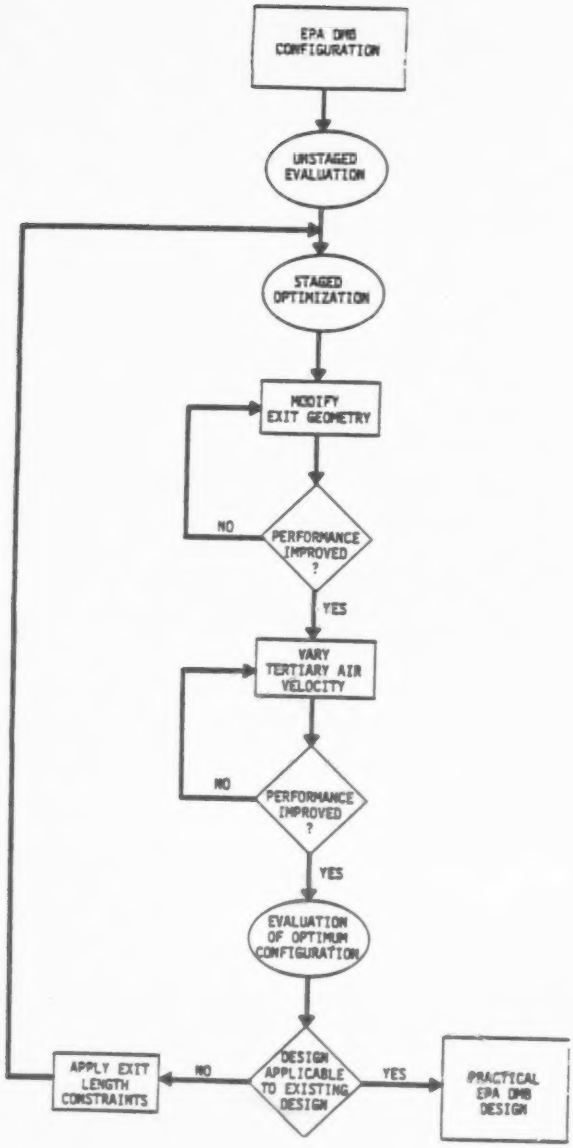

EPA DMB CONFIGURATION
UNSTAGED EVALUATION
STAGED OPTIMIZATION
MODIFY EXIT GEOMETRY
NO
PERFORMANCE IMPROVED ?
YES
VARY TERTIARY AIR VELOCITY
NO
PERFORMANCE IMPROVED ?
YES
EVALUATION OF OPTIMUM CONFIGURATION
APPLY EXIT LENGTH CONSTRAINTS
NO
DESIGN APPLICABLE TO EXISTING DESIGN
YES
PRACTICAL EPA DMB DESIGN

Figure 3-36. Approach for final DMB tests in the LWS.

installation are discussed in subsection 3.5.5. Finally, subsection 3.5.6 compares the performance of all of the DMBs.

3.5.1 Final Prototype DMB Design

The final prototype DMB utilized the same windbox and commercial burner hardware (coal inlet, core air passage, coal nozzle, and secondary air registers) as the other prototype DMB. A sketch of the burner design is shown in Figure 3-37. Modifications were made to the test burner, the DMB with FW parameters, to match the EPA design criteria. These modifications included:

1. Fabrication of a two piece cast refractory burner exit to vary exit length from an exit length-to-diameter ratio (L/D) of 1.0, specified by the DMB design criteria, to an L/D of 0.4, which is more compatible with the short windbox depths and close burner spacing in many pre-NSPS units.

2. Burner throat diameter sized to match the DMB criteria secondary air velocity, 60 ft/sec.

3. Secondary air divider modified to achieve equal velocities through the two passages with 40 percent of the secondary air flow through the inner passage and 60 percent through the outer passage. The initial prototype DMB was designed with a secondary air flow split of 31 percent through the inner secondary air passage and 69 percent through the outer passage.

4. The tertiary air ports were relocated symmetrically around the burner exit, a radial distance of two throat diameters from the burner center. This radial spacing was somewhat less than the DMB design criteria of 2.2 throat diameters, but was the maximum spacing that would fit within the existing windbox. The front wall arrangement is shown in Figure 3-38.

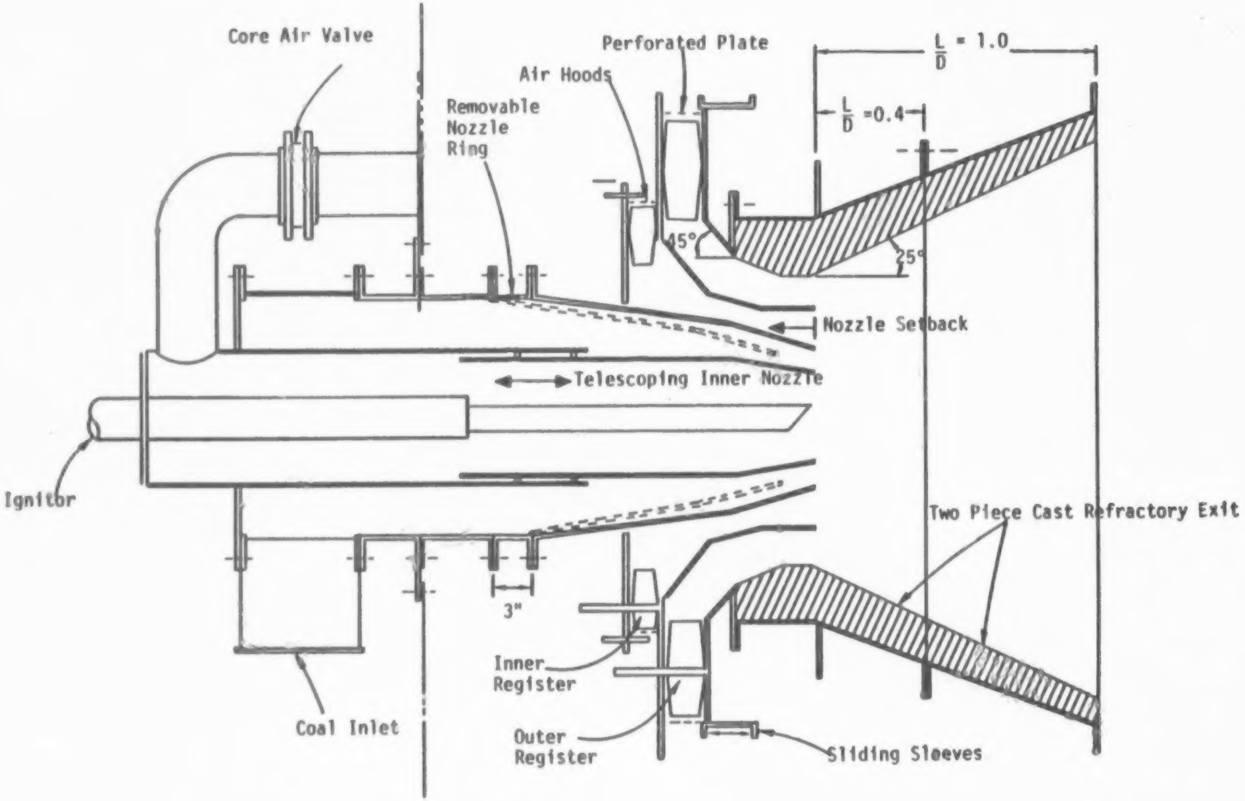

Core Air Valve
Perforated Plate
Air Hoods
Removable Nozzle Ring
L/D = 1.0
L/D =0.4
45°
25°
Nozzle Setback
Telescoping Inner Nozzle
Ignitor
Two Piece Cast Refractory Exit
3"
Inner Register
Outer Register
Coal Inlet
Sliding Sleeves

Figure 3-37. Cross section of final prototype burner design without tertiary air ports.

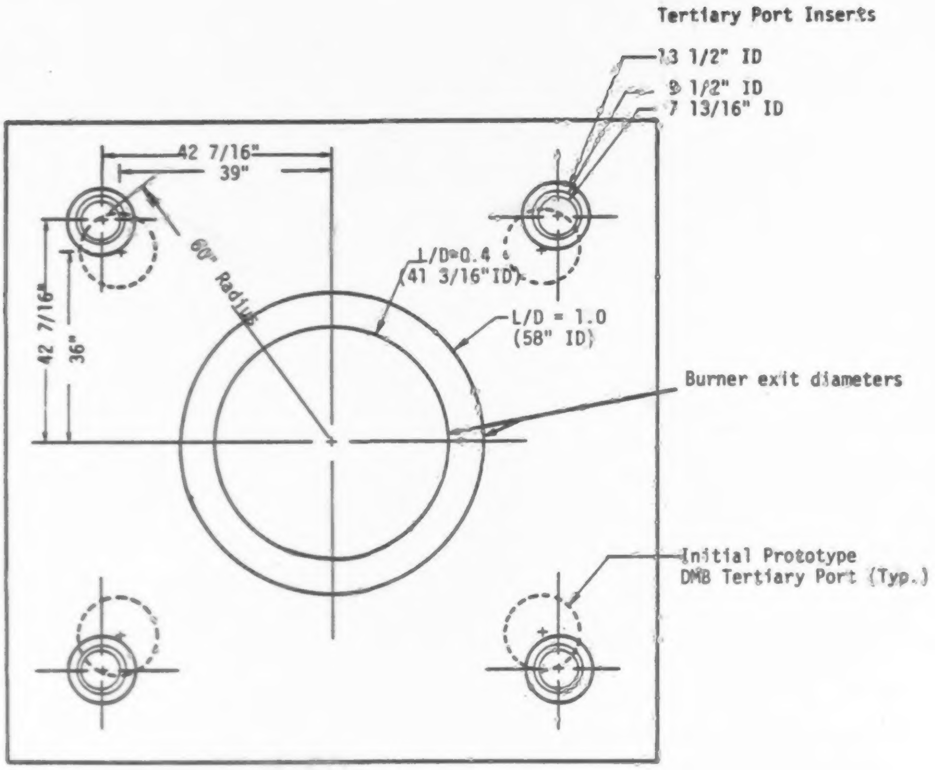

Tertiary Port Inserts
13 1/2" ID
9 1/2" ID
7 13/16" ID
42 7/16"
39"
60" Radius
L/D=0.4
(41 3/16" ID)
L/D = 1.0
(58" ID)
Burner exit diameters
42 7/16"
36"
Initial Prototype
DMB Tertiary Port (Typ.)

Figure 3-38. Front wall arrangement for final prototype DMB development tests.

5. Tertiary port inserts were fabricated to achieve design point velocities (SR_B=70 percent theoretical air) of 50, 100, and 150 ft/sec.

Several modifications were also made to facilitate testing. The internal windbox tertiary air control valves and flowmeters were removed and replaced with ports metered individually by external venturi flowmeters and controlled by remote-operated valves. The venturi flowmeters were more accurate than the internal devices, and the remote valves permitted easier flow control and balancing. Finally, rigid control shafts were installed on the bottom of each secondary air sleeve to minimize misalignment of the sleeves during adjustments.

3.5.2 Unstaged Performance of the Long Exit Configuration

The initial long exit configuration exit length to throat diameter ratio of 1.0 and nozzle setback = 0.0 was first evaluated unstaged to define the operational limits of the burner. A brief parametric matrix of register and core air valve adjustments was completed. The effect of register position on unstaged performance is summarized in Figures 3-39 and 3-40. Opening both the inner and outer registers decreased NO_x emissions. However, the outer register had the greater effect. NO_x levels decreased at a rate of about 1.9 ppm/degree open for the inner register while for the outer register the rate of decrease was about 4.7 ppm/degree. During these unstaged tests, the secondary air sleeves remained 100 percent open, so the distribution of air between the two secondary air passages varied for each combination of inner and outer register vane positions. Not only does the outer secondary air passage have a 50 percent larger exit area than the inner secondary passage, but the outer register is substantially larger than the inner register. Thus, a change in the restriction in the outer secondary passage would have a greater effect than a similar change in the inner passage. This accounts for the greater effect on NO_x emissions by the outer register. Register position had no significant effect on flame length or CO levels.

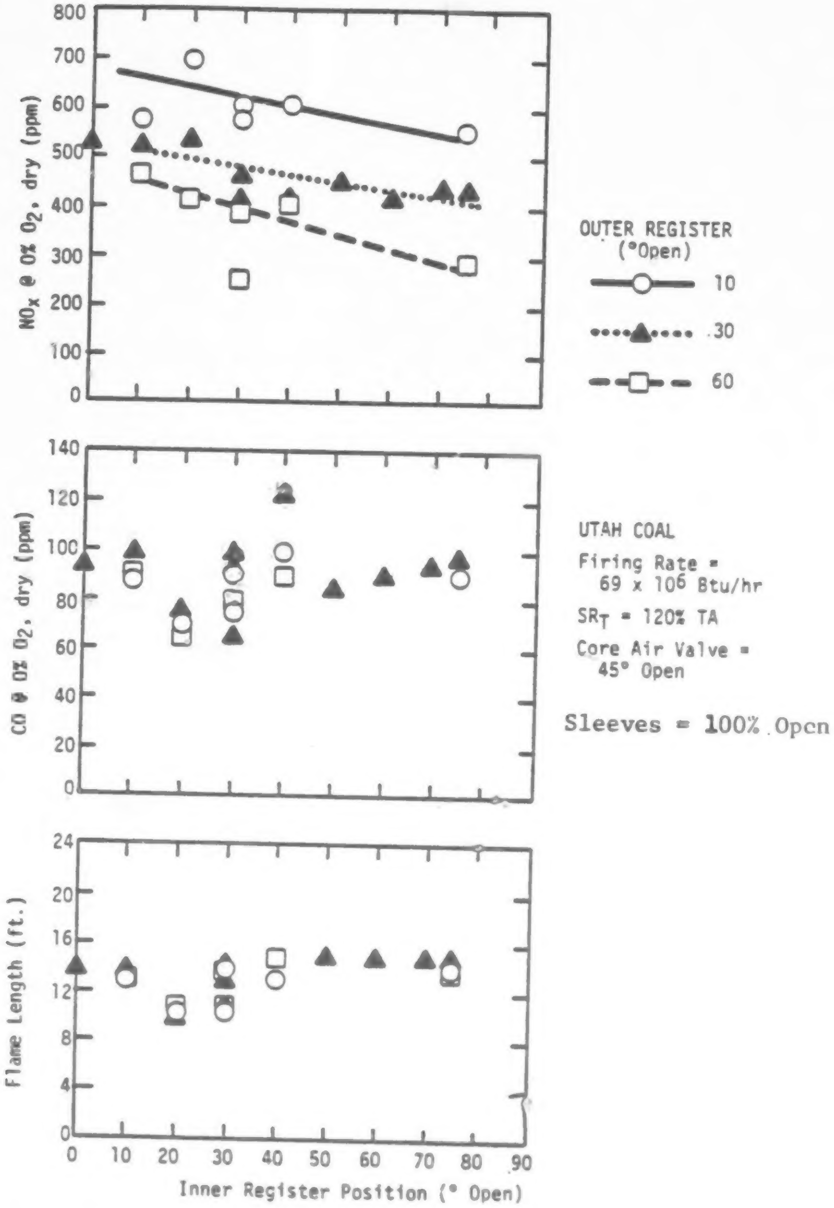
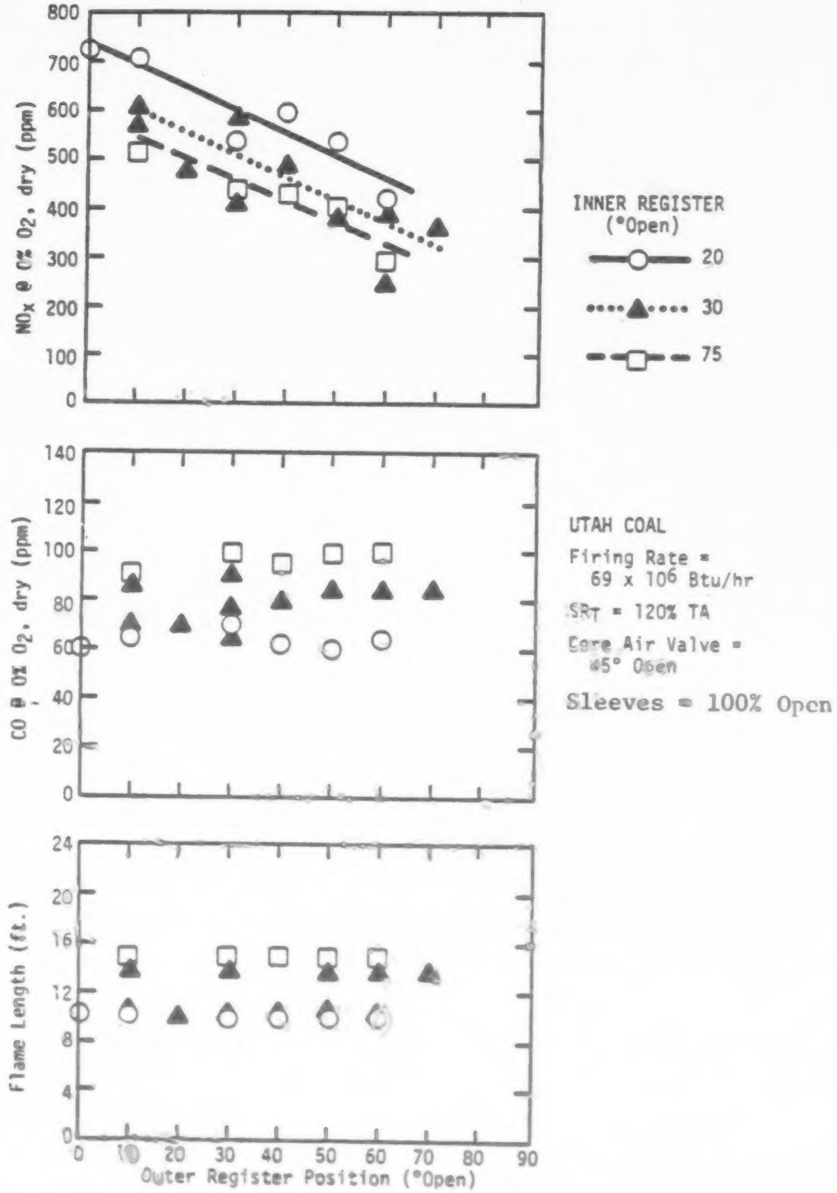


Figure 3-39. Effect of inner register position on unstaged performance of the initial long exit DMB configuration.



UTAH COAL

Firing Rate = 69 x 10^6 Btu/hr

SR_T = 120% TA

Core Air Valve = 45° Open

Sleeves = 100% Open

Figure 3-40. Effect of outer register position on unstaged performance of the initial long exit DMB configuration.

The position of the core air valve, and thus the core air flow rate had a slight effect on NO_x emissions, but had little effect on CO. The data for the unstaged tests are summarized in Figure 3-41. A stable flame could be maintained for the entire range of motion of the core air valve, from fully open (90° open) to closed (0° open). NO_x increases as the core air valve is opened at a rate of about 1 ppm/degree open. Visual observation indicated that a core valve position of 10° open provided the best stability.

In summary, the initial long exit DMB configuration could be operated over a wide range of adjustments under unstaged conditions. Stable flames could be maintained over the following ranges:

Core air valve = 0 - 90° open
Inner register = 0 - 75° open
Outer register = 0 - 60° open

3.5.3 Staged Optimization of the Long Exit Configuration

Staged optimization tests began with the initial, DMB criteria-based exit configuration, exit L/D = 1.0 and primary setback = 0.0 in. The optimization tests followed a detailed parametric matrix, of the following parameters:

- Primary air velocity
- Core air flow
- Secondary air swirl for both inner and outer passages
- Air flow distribution between the two secondary air passages

Burner settings were optimized firing Utah coal at full-load under staged operation with a burner zone stoichiometry of 70 percent and with 20 percent excess air.

Overall, burner performance was relatively insensitive to burner adjustments under staged conditions within stable operating ranges. The effect of core air flow, inner secondary swirl, and outer secondary swirl

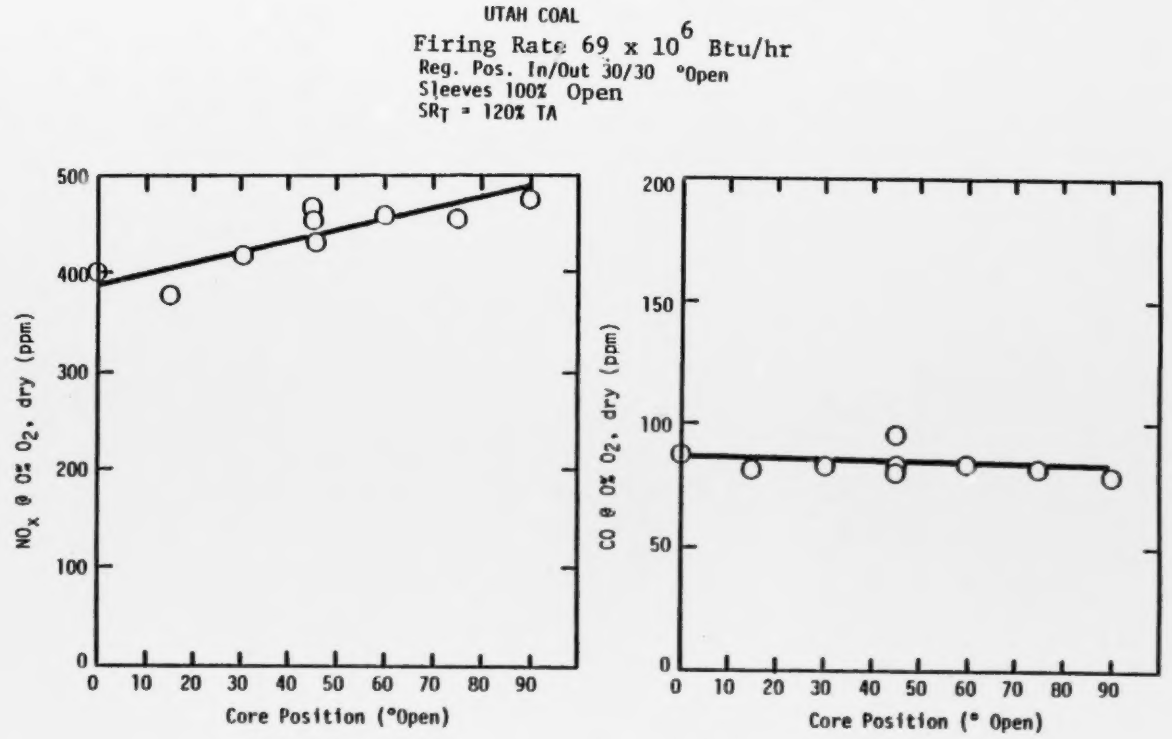
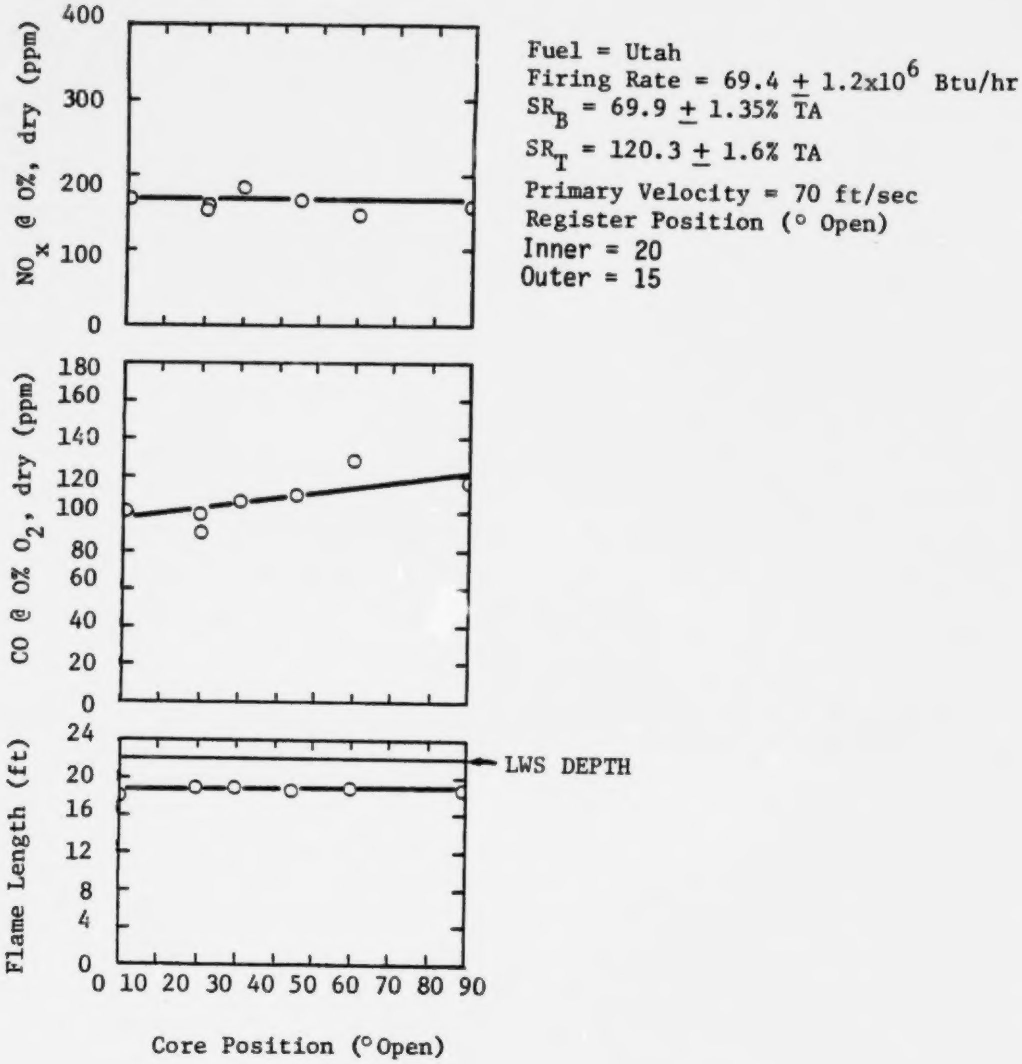


Figure 3-41. Effect of core valve position on unstaged performance of the initial long exit DMB configuration.

were similar over a range of primary velocities. Typical examples of these effects are illustrated in Figures 3-42, 3-43 and 3-44 respectively, for a nominal primary velocity of 70 ft/sec. As in the case of unstaged operation, a stable flame could be maintained for the entire range of motion of the butterfly valve which controls the core air flow rate. NO_x emissions and flame length were basically unaffected by variations in core air flow, although levels of CO increased as the core air valve was opened. Decreasing the swirl to the inner secondary air passage by opening the inner register tended to decrease NO_x at a rate of about 1.2 ppm/degree open. Combustion efficiency , as indicated by CO emissions, decreased at inner register positions more than 25-30 degrees open. The best performance was achieved with the inner register vanes at about 20 degrees open. NO_x emissions also decreased by opening the outer register vanes, as shown in Figure 3-44. The effect under staged conditions, however, was considerably less (2.25 ppm/degree open) than for the previous unstaged tests (4.7 ppm/degree). CO emissions were very sensitive to outer register position with outer secondary register vane angles restricted to less than 20 degrees open to achieve relatively low CO levels.

The optimum settings for arrange of primary velocities were similar and are summarized in Table 3-9. The effects of burner zone stoichiometry on NO_x and CO emissions, illustrated in Figure 3-45, were essentially the same for all three primary velocities. NO_x emissions leveled off abruptly at burner zone stoichiometries less than 70 percent, with stable, but lazy flames maintained down to a 53 percent. CO emissions remained constant down to about 75 percent, then increased. The excess air characteristics, summarized in Figure 3-46, were also comparable for the three optimum conditions at an SR_B if 70 percent. The average rate of decrease in NO_x was about 7 ppm/percent theoretical air. Relatively low CO could be maintained down to about 14 percent excess air.

This initial long exit maintained flame stability over a wide range of excess air, burner zone stoichiometry, and burner adjustments. The range of burner adjustments increased at lower primary velocities with no significant effect on emissions. Acceptable flame length, less than 22 feet, was



Fuel = Utah
Firing Rate = 69.4 ± 1.2×10^6 Btu/hr
SR_B = 69.9 ± 1.35% TA
SR_T = 120.3 ± 1.6% TA
Primary Velocity = 70 ft/sec
Register Position (° Open)
Inner = 20
Outer = 15

Figure 3-42. Effect of core air on air staged performanced for initial long exit DMB configuration.

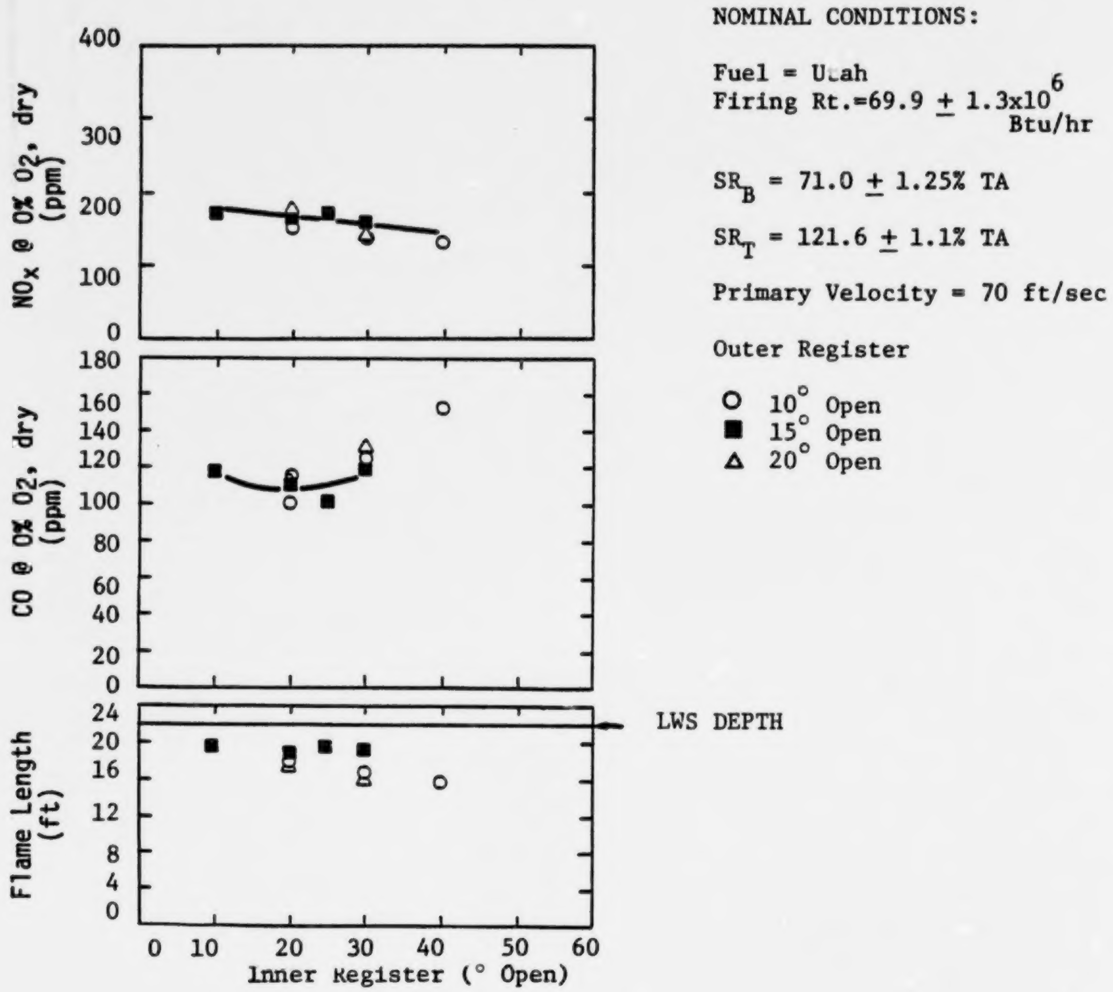


Figure 3-43. Effect of inner register on staged performance for initial long exit DMB configuration.

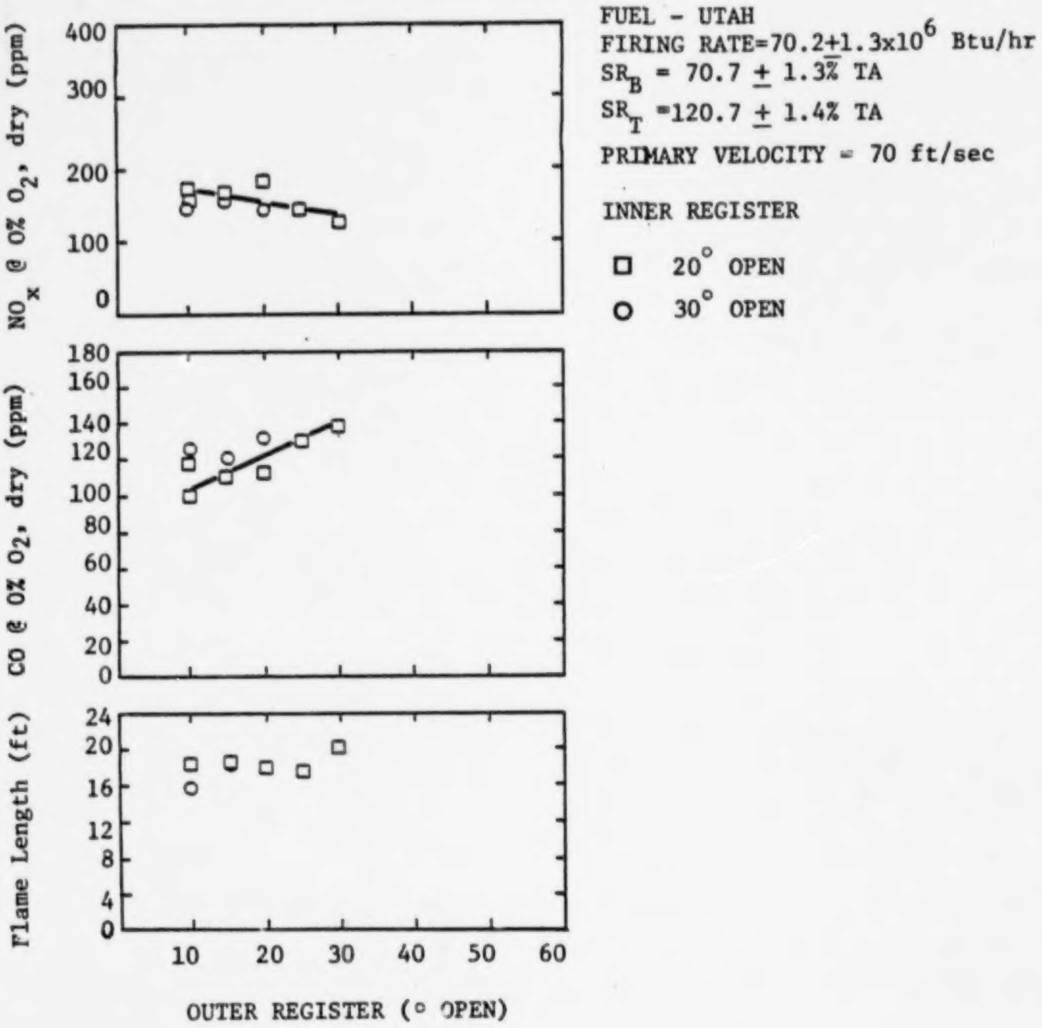


Figure 3-44. Effect of outer register on staged performance for initial long exit configuration.

flame length were basically unaffected by variations in core air flow, although levels of CO increased as the core air valve was opened. Decreasing the swirl to the inner secondary air passage by opening the inner register tended to decrease NO_x at a rate of about 1.2 ppm/degree open. Combustion efficiency , as indicated by CO emissions, decreased at inner register positions more than 25-30 degrees open. The best performance was achieved with the inner register vanes at about 20 degrees open. NO_x emissions also decreased by opening the outer register vanes, as shown in Figure 3-44. The effect under staged conditions, however, was considerably less (2.25 ppm/degree open) than for the previous unstaged tests (4.7 ppm/degree). CO emissions were very sensitive to outer register position with outer secondary register vane angles restricted to less than 20 degrees open to achieve relatively low CO levels.

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This initial long exit maintained flame stability over a wide range of excess air, burner zone stoichiometry, and burner adjustments. The range of burner adjustments increased at lower primary velocities with no significant effect on emissions. Acceptable flame length, less than 22 feet, was achieved with a bulbous-shaped flame that completely filled the burner exit. A layer of slag began forming on the last third of the exit after 2-3 days of testing, slowly building up in thickness. This had been predicted by Foster Wheeler and is a principal reason for using short exit designs in field operating boilers. Discolorations of the refractory exit indicated that some

TABLE 3-9. SUMMARY OF OPTIMUM CONDITIONS FOR THE INITIAL LONG EXIT DMB CONFIGURATION

PRIMARY VELOCITY (ft/sec)	CORE VALVE (°Open)	INNER REGISTER (° Open)	OUTER REGISTER (°Open)	INNER SLEEVE (% Open)	OUTER SLEEVE (% Open)
Lower	45	20	10	100	100
70	20	20	15	50	50
Higher	45	20	10	100	100

NOMINAL CONDITIONS:
Fuel - Utah
Firing Rate = 70.3 ± 2.4 x 10^6 BTU/hr
SR_T + 120.4 ± 1.9% TA

	Primary Velocity (ft/sec)	Register Pos. In/Out (°Open)	Core (°Open)
□	Lower	20/10	45
○	70	20/15	20
△	Higher	20/10	45

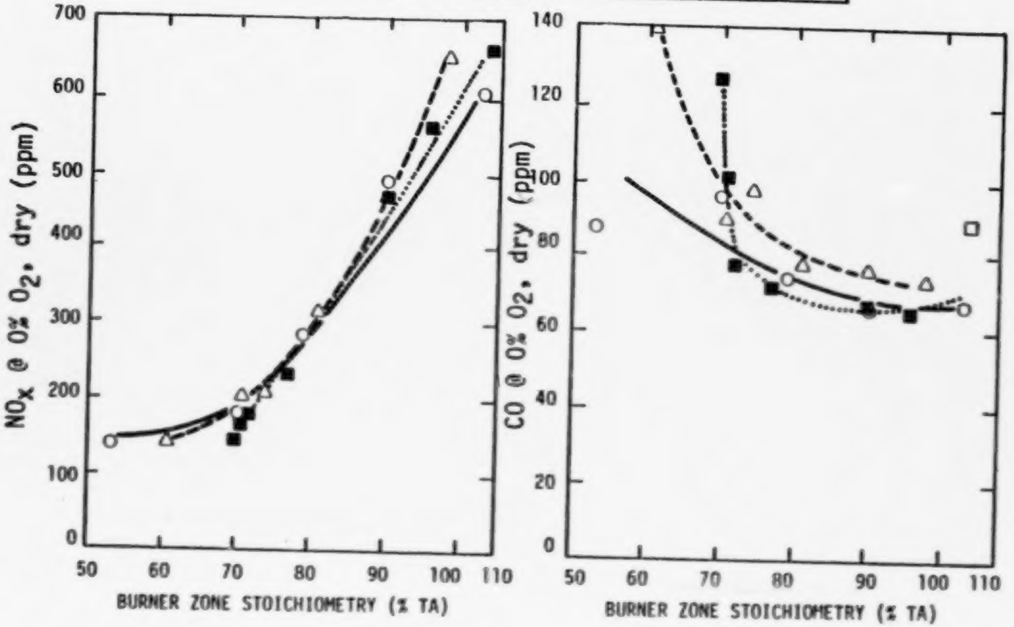


Figure 3-45. Effect of staging on burner performance for the initial long exit configuration.

NOMINAL CONDITIONS:

FUEL - Utah
FIRING RATE - $69.6 \pm 2.3 \times 10^6$ Btu/hr
SR_B = 70.3 ± 22% T.Ā.
Setback = 0
4D = 1.0

	Primary Velocity (ft/sec)	Register Position In/Out (° Open)	Core (° Open)
□	50	20/10	45
○	75	20/15	20
△	85	20/10	45

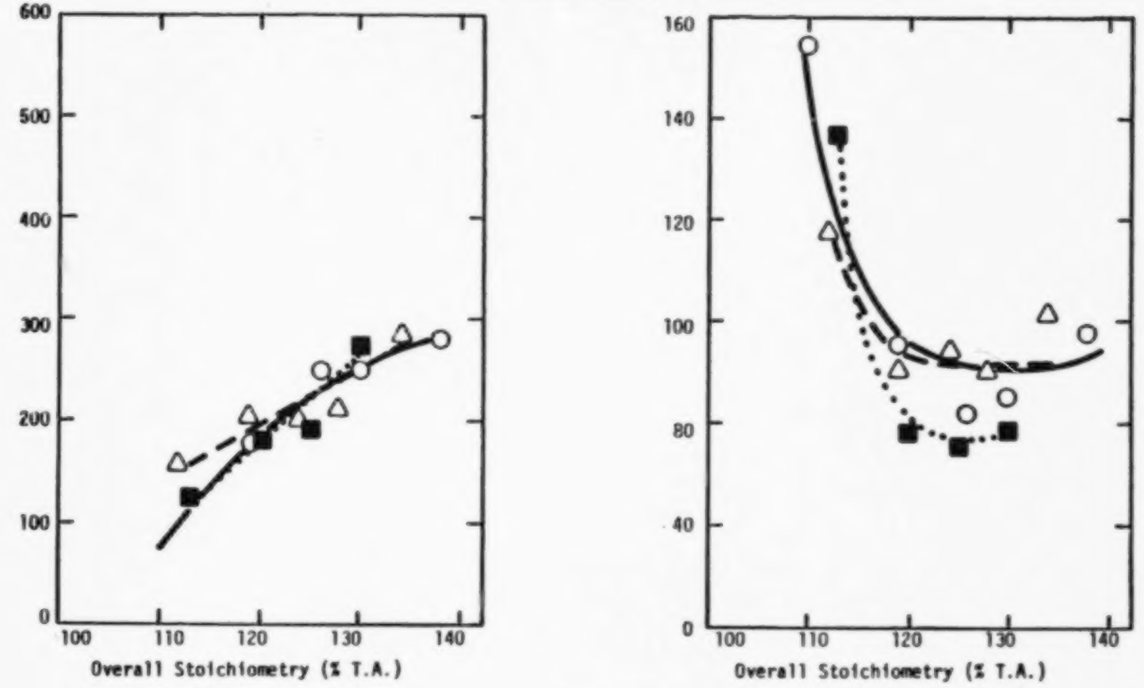


Figure 3-46. Effect of excess air for the initial long exit configuration.

achieved with a bulbous-shaped flame that completely filled the burner exit. A layer of slag began forming on the last third of the exit after 2-3 days of testing, slowly building up in thickness. This had been predicted by Foster Wheeler and is a principal reason for using short exit designs in field operating boilers. Discolorations of the refractory exit indicated that some flame impingement may have occurred. The relatively high CO levels at $SR_B <$ 70 percent, as well as high measured fly ash carbon content (15-20 percent) at these conditions indicate that flame impingement on the exit may have caused some quenching.

Additional tests were conducted with the long exit and a nozzle setback of 3.0 in. The objective was to produce a flame which did not impinge on the exit. As in the initial tests, burner performance was insensitive to burner adjustments under staged conditions within stable operating ranges. Optimum performance was obtained with both the inner and outer registers less than 20 degrees open. Figure 3-47 summarizes the staged performance of the long exit with a setback of 3.0 in. As in the case of a setback of 0.0 inches, the characteristic staging curves for NO_x and CO are nearly identical for the primary velocity range evaluated. Moreover, NO_x emissions for the increased setback configuration match the emissions from the initial 0.0 inch setback case. Also emissions were also relatively insensitive to excess air for the increased setback configuration. As shown in Figure 3-48, NO_x emissions were independent of primary velocity. The average rate of decrease was 3 ppm/ percent excess air, less than for the initial configuration with a setback of 0.0 in. Differences in CO levels, however, were somewhat greater with the lowest levels achieved with at the primary velocity of 70 ft/sec. Increasing the setback had essentially no effect on emissions, but it did provide added stability over a slightly wider range of burner adjustments.

Optimum performance was obtained for the long exit, L/D = 1.0 was obtained at the following burner settings:

Primary setback	3 in.
Primary velocity	70 ft/sec
Core air valve	45^0 open

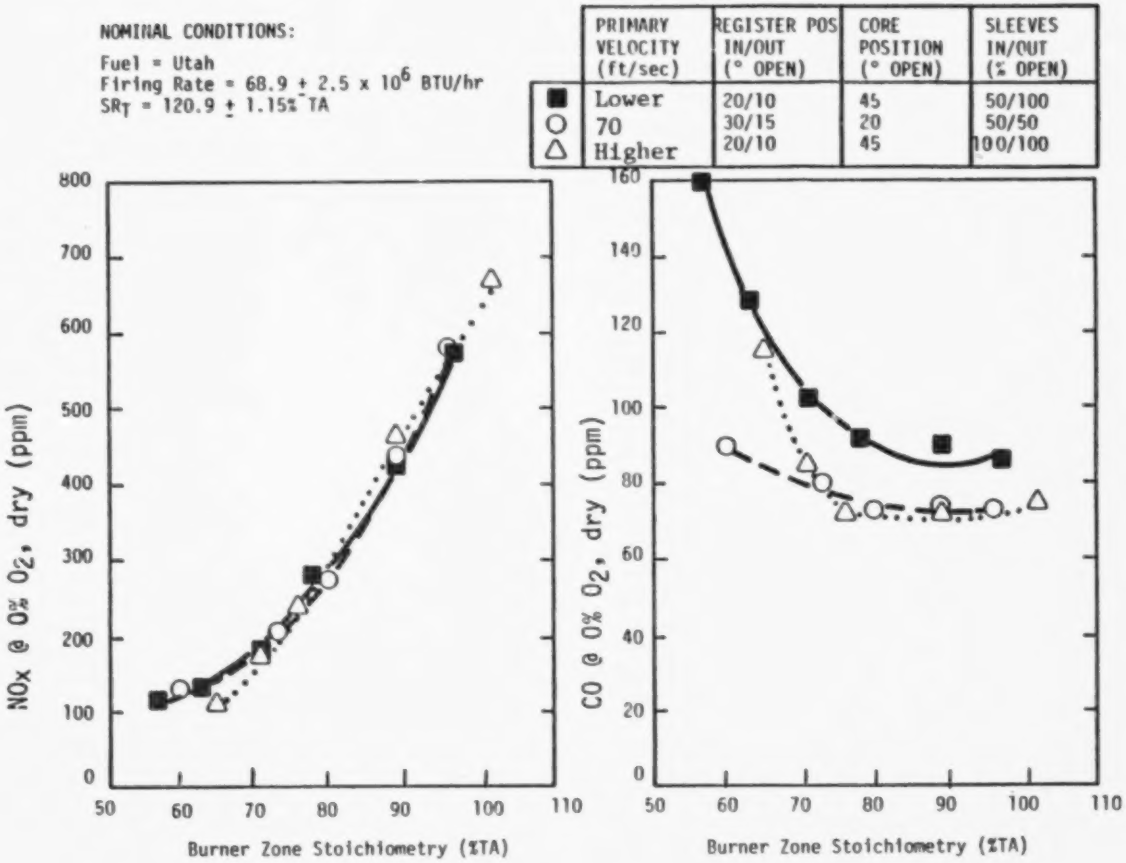


Figure 3-47. Effect staging on burner performance with long exit and primary setback = 3.0 in.

Nominal Conditions:
Fuel = Utah
Firing Rate = 68.8 ± 1.82 x 10^6 Btu/hr
SR_B = 70.2 ±1.6% TA

	Primary Velocity (ft/s)	Register Position In/Out (° Open)	Core Valve Position (° Open)	Sleeves In / Out (% Open)
■	55	20/10	45	50/100
○	75	50/15	20	50/50
△	85	20/10	45	100/100

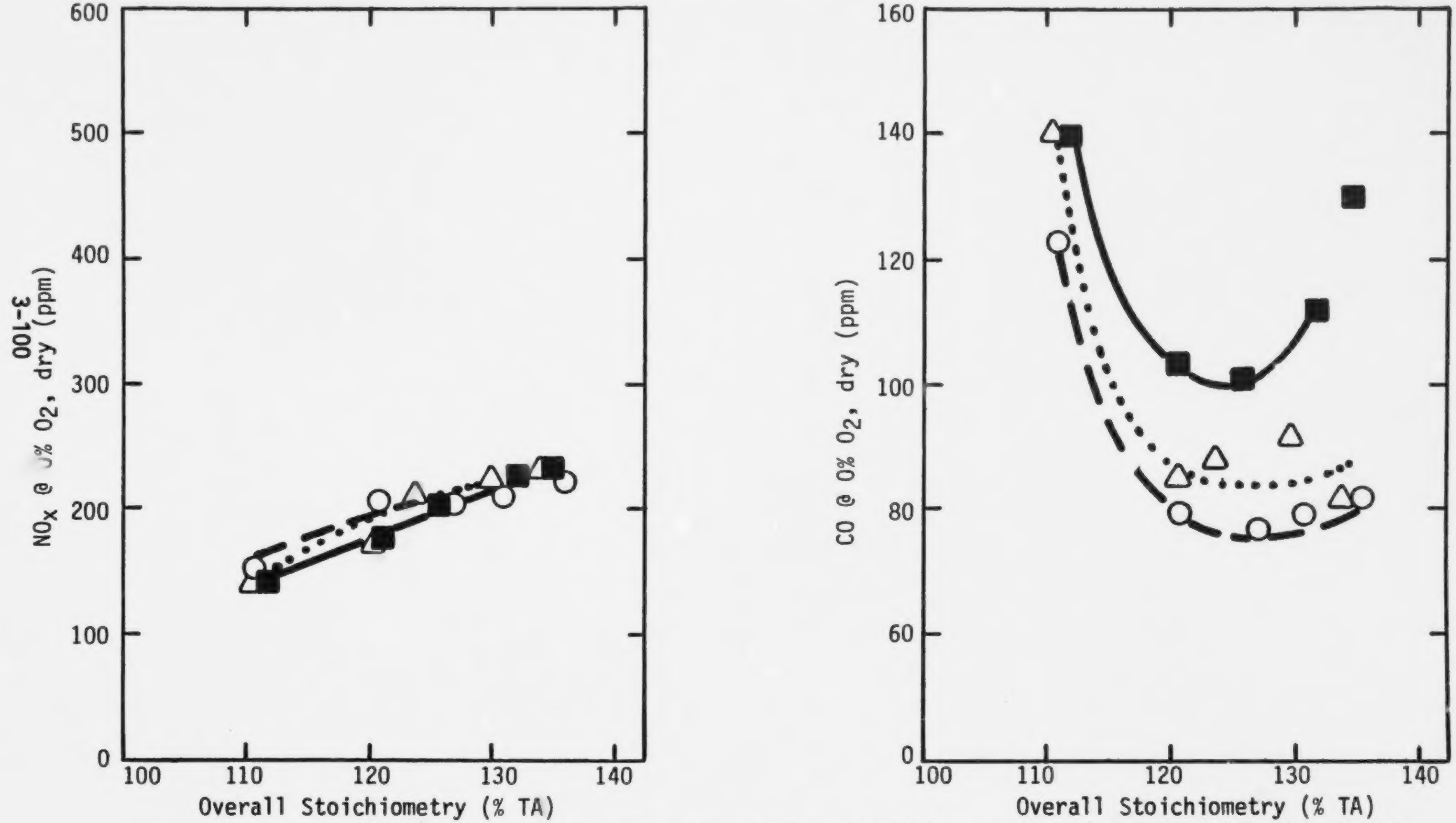


Figure 3-48. Effect of excess air on staged performance with long exit and primary setback = 3.0 in.

Inner register	10° open
Outer register	20° open
Secondary air sleeve	100% open

Burner performance was verified over a wide range of firing rates, shown in Figure 3-49. The burner could be operated down to 35×10^6 Btu/hr maintaining a burner zone stoichiometry of 70 percent without loss of flame. NO_x emissions decreased with load to about 40×10^6 Btu/hr and then increased abruptly. Flame stability was marginal below 40×10^6 Btu/hr, resulting in variations in measured NO_x emissions of about 50 ppm. This was probably due to the decrease in secondary velocity required to maintain burner zone stoichiometry as was illustrated in Figure 3-30. However, CO emissions, increased steadily as load decreased.

3.5.4 Optimization of Short Exit Configuration

Following the optimization and evaluation of the DMB design criteria-based long exit burner, a section of the two-piece exit was removed to provide an exit length-to-throat diameter ratio of 0.4. This exit length would be more suitable for applications on pre-NSPS boiler designs. Because of the slightly wider operating range achieved during the long exit tests, the setback of 3.0 in. was retained for the short exit optimization. Again, Utah coal was used for the optimization tests. The optimum settings for staged operation of the long exit design were used as a baseline and then adjusted as required to improve performance.

As with the long exit design, burner performance was relatively insensitive to burner adjustments under staged conditions within the ranges investigated. The effects of core air flow, inner register position, and outer register position on burner performance are shown in Figure 3-50, 3-51 and 3-52 respectively. Core air flow, as indicated by core air valve position, had only slight effects on emissions. Minimum NO_x emissions were achieved with the valve between 40 and 60° open. There was no effect on CO emissions or flame characteristics. The degree of swirl to the inner secondary air passage had no measurable effect on burner performance during

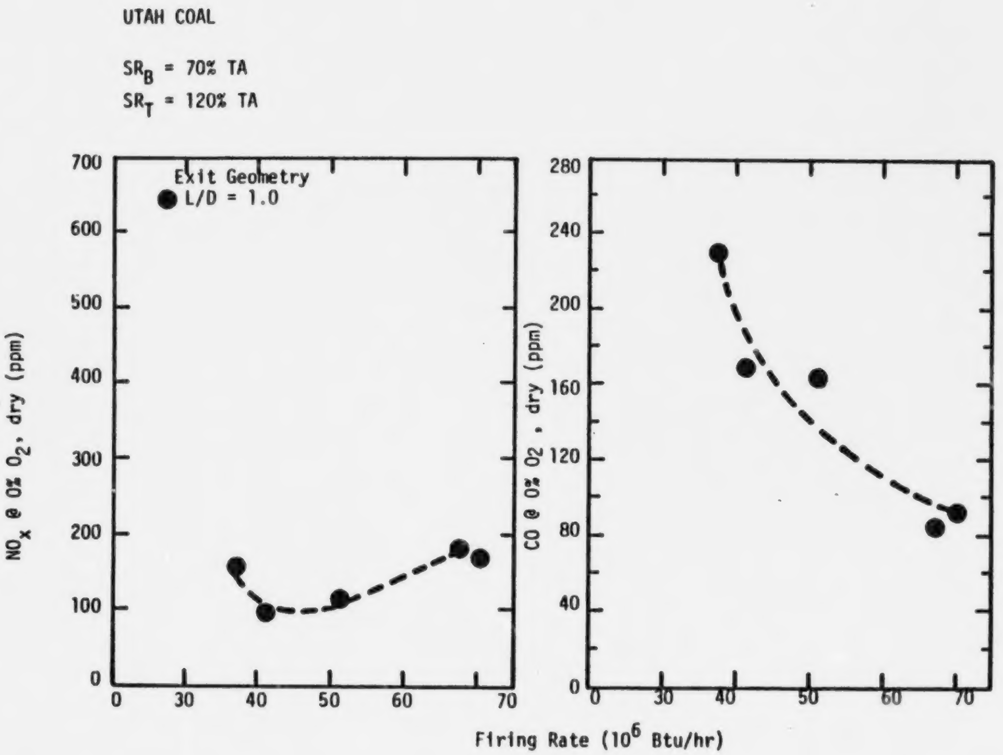
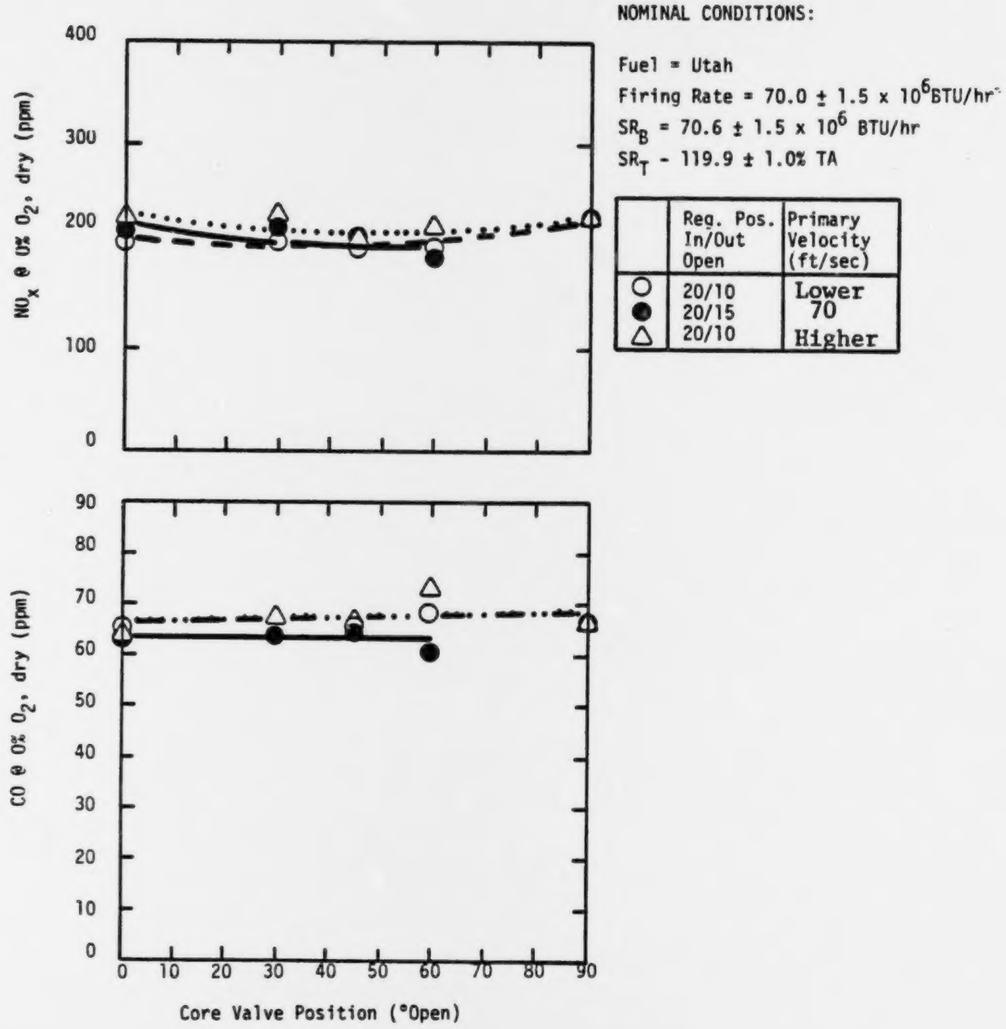


Figure 3-49. Effect of firing rate on optimum long exit industrial prototype DMB performance.



NOMINAL CONDITIONS:

Fuel = Utah
Firing Rate = 70.0 ± 1.5 x 10^6BTU/hr
SR_B = 70.6 ± 1.5 x 10^6 BTU/hr
SR_T - 119.9 ± 1.0% TA

	Reg. Pos. In/Out Open	Primary Velocity (ft/sec)
○	20/10	Lower
●	20/15	70
△	20/10	Higher

Figure 3-50. Effect of core position on staged performance for short exit DMB configuration.

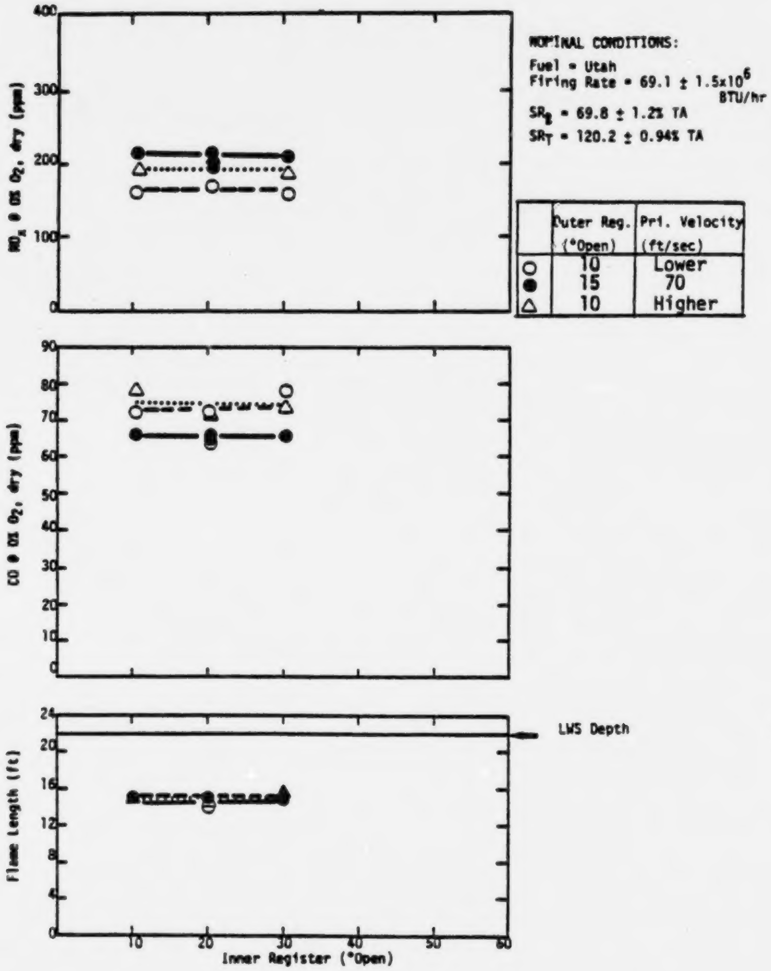
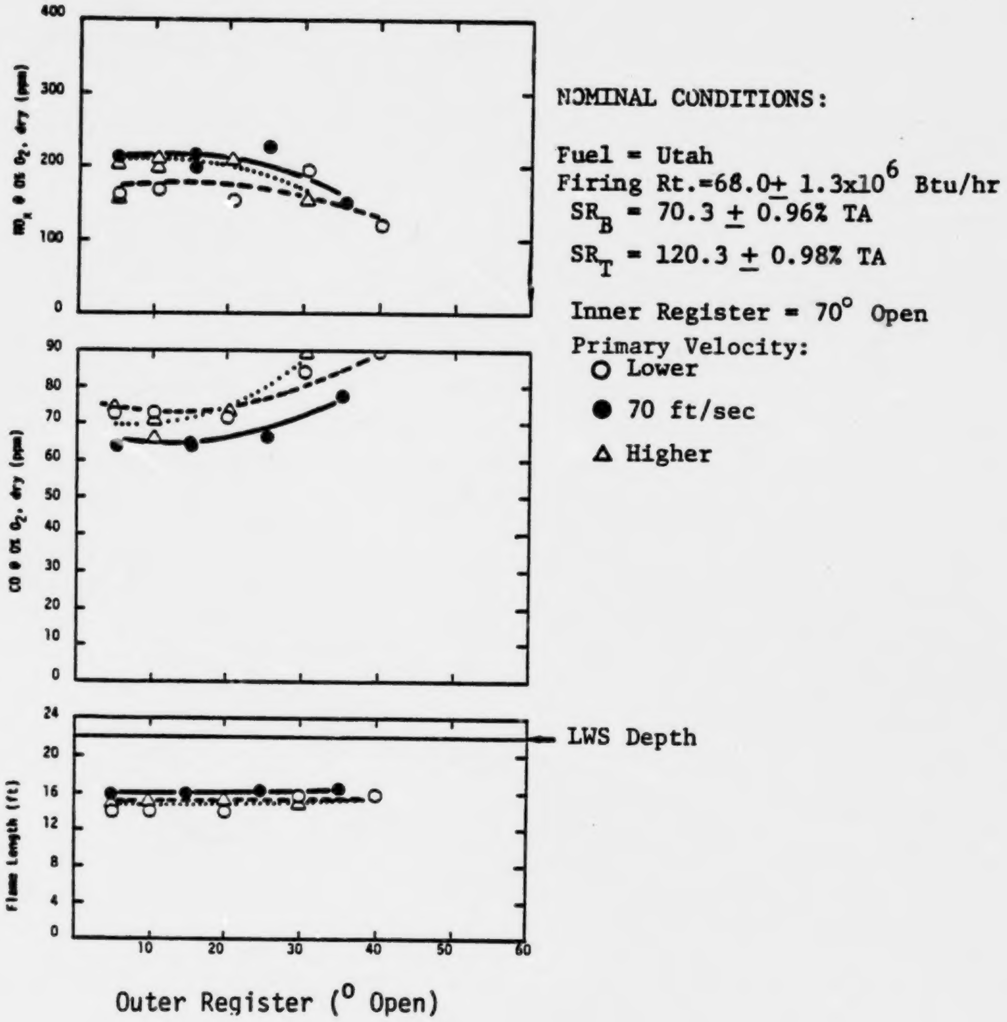


Figure 3-51. Effect of inner register adjustment on staged performance for short exit DMB configuration.



NOMINAL CONDITIONS:

Fuel = Utah
Firing Rt.=68.0 ± 1.3x10^6 Btu/hr
SR_B = 70.3 ± 0.96% TA
SR_T = 120.3 ± 0.98% TA

Inner Register = 70° Open
Primary Velocity:
○ Lower
● 70 ft/sec
△ Higher

Figure 3-52. Effect of outer register adjustment on a staged performance for short exit DMB configuration.

these staged tests of the short exit DMB. However, burner performance was affected by the position of the outer register position. Opening the outer register more than 20^{o} open resulted in a decrease in NO_x along with an increase in CO emissions. These affects are comparable to those observed during the tests with the long exit configuration.

The characteristic staging curves for NO_x and CO emissions from the short exit burner are shown in Figure 3-53. As in the case of the long exit design, there was no effect of primary velocity on NO_x emissions. NO_x decrease at about 16 ppm/percent T.A. as the staging was increased. Below the design point, burner zone stoichiometry of 70 percent, the NO_x emissions leveled off. CO emissions remained relatively constant down to a burner zone stoichiometry of 70 percent before increasing significantly. The emissions from the short exit DMB were insensitive to excess air, as shown in Figure 3-54. Again, there was no effect of primary velocity on NO_x emissions. NO_x emissions decreased 5 ppm for every percent decrease in excess air. CO levels remained low down to about 16 percent excess air before increasing significantly.

Although there was no measurable difference in performance (NO_x and CO emissions) for the range of primary velocities tested, the sensitivity of flame stability to burner adjustments varied with primary velocity. The high velocity case was most sensitive to burner adjustments. The burner parameters that provided the best performance over the widest operating range for the short exit configuration are listed in Table 3-10. The optimum settings for this short exit design are similar to the long exit configuration. These burner settings were used for verification and LIMB tests.

The short exit DMB produced significantly higher NO_x emissions firing the Indiana coal than with Utah coal under similar test conditions. The data are compared in Figure 3-55. At the design point burner zone stoichiometry (SR_B) of 70 percent T.A., NO_x emissions from the Indiana coal were 240 ppm, about 50-60 ppm higher than for the Utah coal. However, the effect of staging was similar for both coals down to the design point. Below SR_B = 70

NOMINAL CONDITIONS:

FIRING RATE=70.9 ± 2.8×10^6 BTU/hr.
SR_T= 120.2 ± 1.15% TA
FUEL = UTAH BITUMINOUS

	PRIMARY VELOCITY (ft/sec)	REGISTER POS IN/OUT (° OPEN)	CORE POSITION (° OPEN)	SLEEVES IN/OUT (% OPEN)
■	Lower	20/10	45	50/100
○	70	50/15	20	50/50
△	Higher	20/10	45	50/100

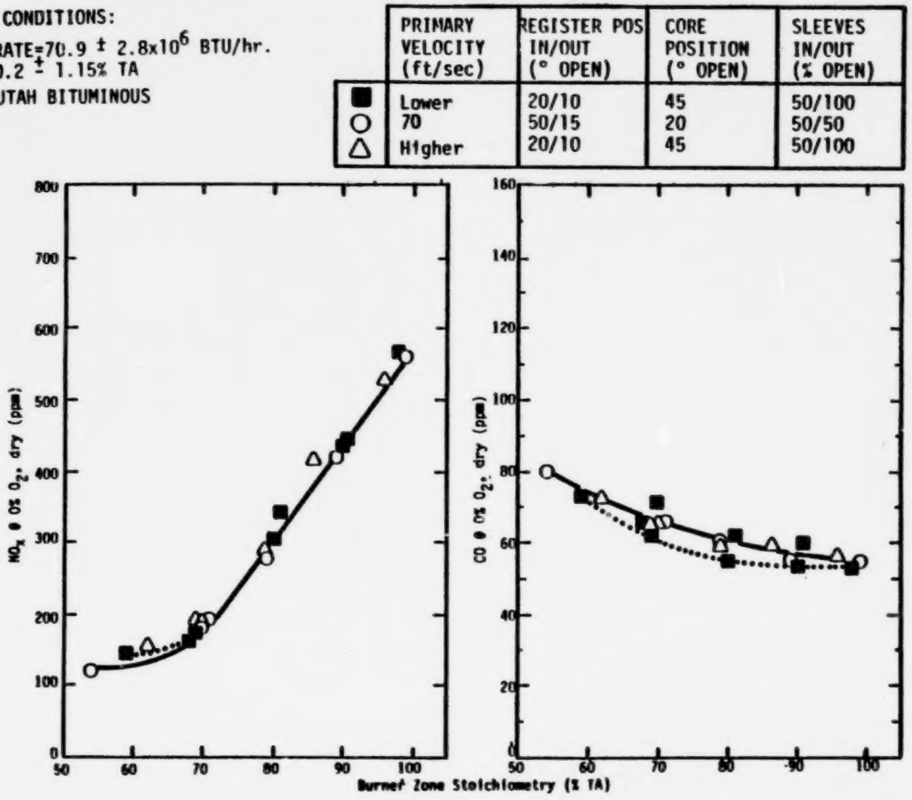


Figure 3-53. Burner performance with short exit (L/D=0.4) and setback = 3.0 in.

NOMINAL CONDITIONS:
FIRING RATE=69.3 ± 1.5x10^6BTU/hr.
SR_B=70.2 ± 0.8% TA
FUEL = UTAH BITUMINOUS

	PRIMARY VELOCITY (ft/sec)	REGISTER POS IN/OUT (° OPEN)	CORE POSITION (° OPEN)	SLEEVES IN/OUT (% OPEN)
■	70	20/15	45	50/50
○	Lower	20/10	60	50/100
△	Higher	20/10	45	100/100

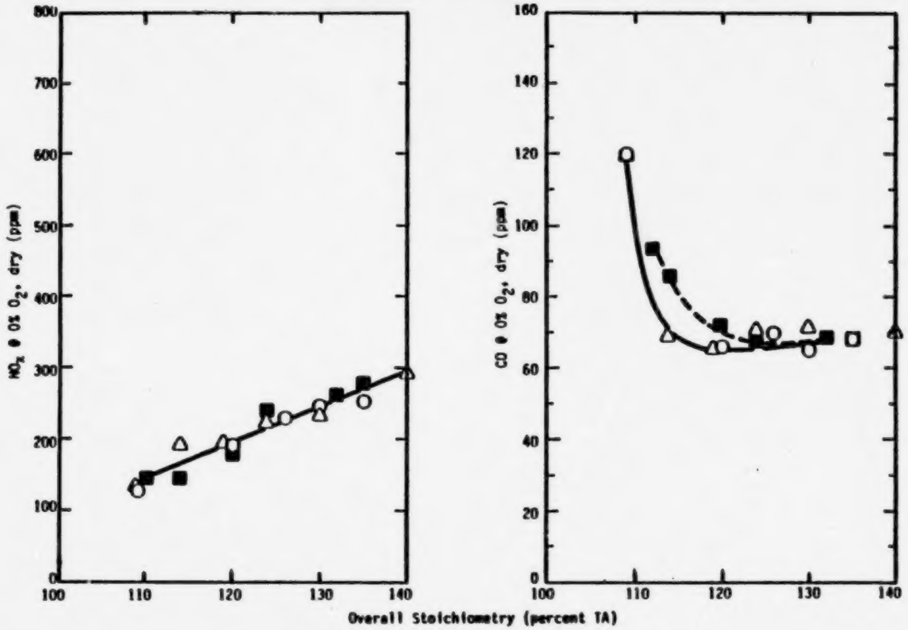


Figure 3-54. Effect of excess air on emissions with short exit configuration.

TABLE 3-10. SUMMARY OF OPTIMUM CONDITIONS FOR PROTOTYPE DMB

EXIT L/D	PRIMARY SETBACK (in)	PRIMARY VELOCITY (ft/sec)	CORE AIR VALVE (° Open)	OUTER REGISTER (° Open)	INNER REGISTER (° Open)	OUTER SLEEVE (% Open)	INNER SLEEVE (% Open)
1.0	3	70	45	20	10	100	100
0.4	3	70*	45	20	15	50	50

*DMB Design Point

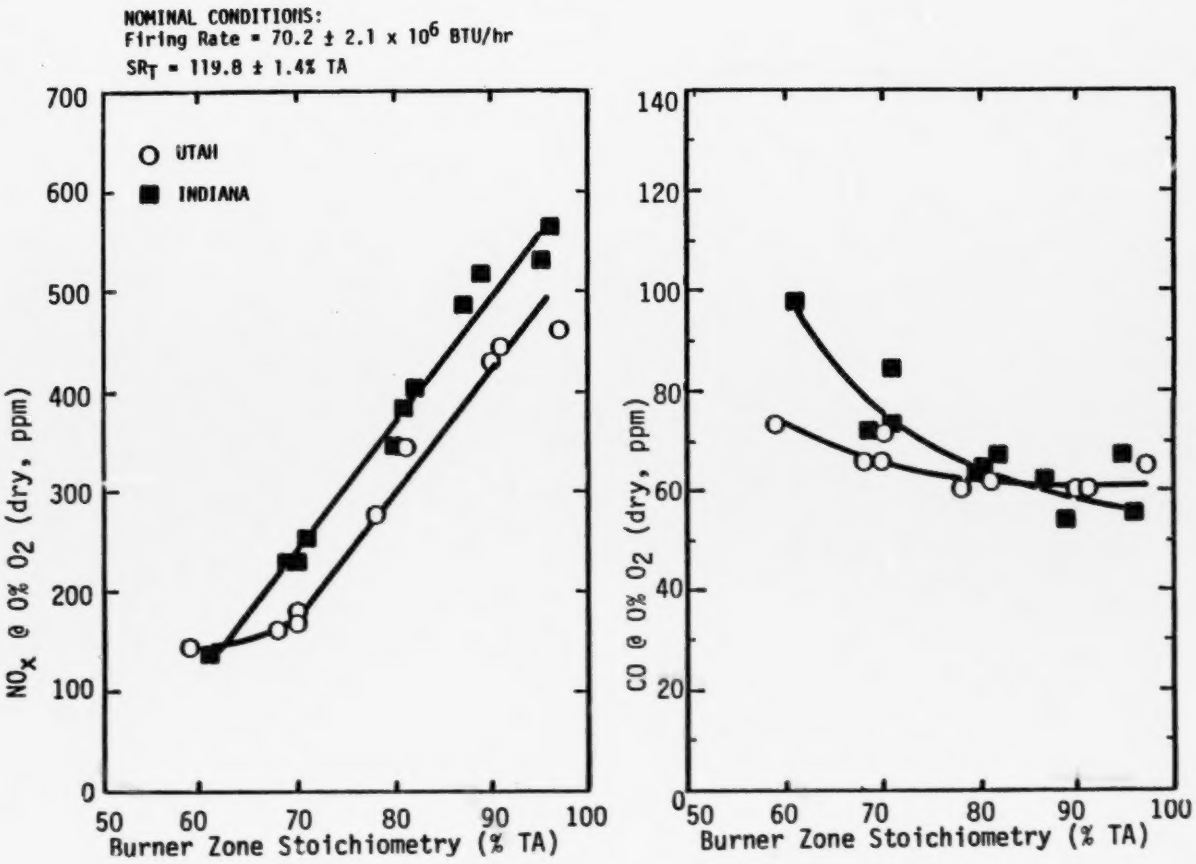


Figure 3-55. Comparison of staged performance of the optimum short exit configuration with Utah and Indiana coal.

percent, the rate of NO_x reduction decreased as staging increased for the Utah coal. No such effect was observed for the Indiana coal down to its stability limit, approximately SR_B = 60 percent. CO emissions produced by the two coals were comparable down to SR_B = 80 percent. Combustion efficiency, as indicated by an increase in CO emissions, decreased for the Indiana coal approaching its stability limit. The CO emissions with Utah coal were relatively insensitive to staging down to SR_B = 60 percent.

The effect of excess air on emissions from the two coals is summarized in Figure 3-56. Again, the trends were similar, with NO_x emissions decreasing at a rate of about 6 ppm/percent T.A. Emissions from the Indiana coal were about 50 ppm higher than those from the Utah coal over the entire range. The characteristic CO curves for the two coals were similar also, with no significant increase in CO occurring down to an overall stoichiometry (SR_T) of about 112 percent. Absolute levels of CO were 10-15 ppm higher for the Indiana coal down to the minimum excess air point.

Measurements of fly ash carbon, summarized in Figure 3-57, indicate that staging and the corresponding decrease in NO_x emissions resulted in a slight decrease in combustion efficiency with the final short exit DMB. Minimum NO_x levels from 147 to 170 ppm were achieved with fly ash carbon content between 12 and 15 percent. Essentially unstaged operation yielded about 560 ppm NO_x with fly ash carbon between 10 and 12 percent. The long exit design achieved comparable levels of NO_x (155 ppm) but with higher measured fly ash carbon, 21 percent, indicating that observed impingement of the flame on the long exit resulted in a burnout problem.

The effect of firing rate on the emissions from the optimum short exit configuration is shown in Figure 3-58. Flame stability was maintained down to about 56 percent of rated firing capacity at staged conditions, SR_B = 70 percent. NO_x emissions decreased monotonically for the short exit DMB as firing rate was decreased. The level of NO_x emissions dropped 40 ppm lower for the short exit than the long exit DMB at less than design firing capacity. However, the NO_x emissions increased for the optimum long exit configuration when the firing rate was reduced to less than 40×10^6 Btu/hr.

NOMINAL CONDITIONS:
Firing Rate = 69.5 ± 1.9 x 10^6 BTU/hr
SR_B = 70.1 ± 1.4% TA

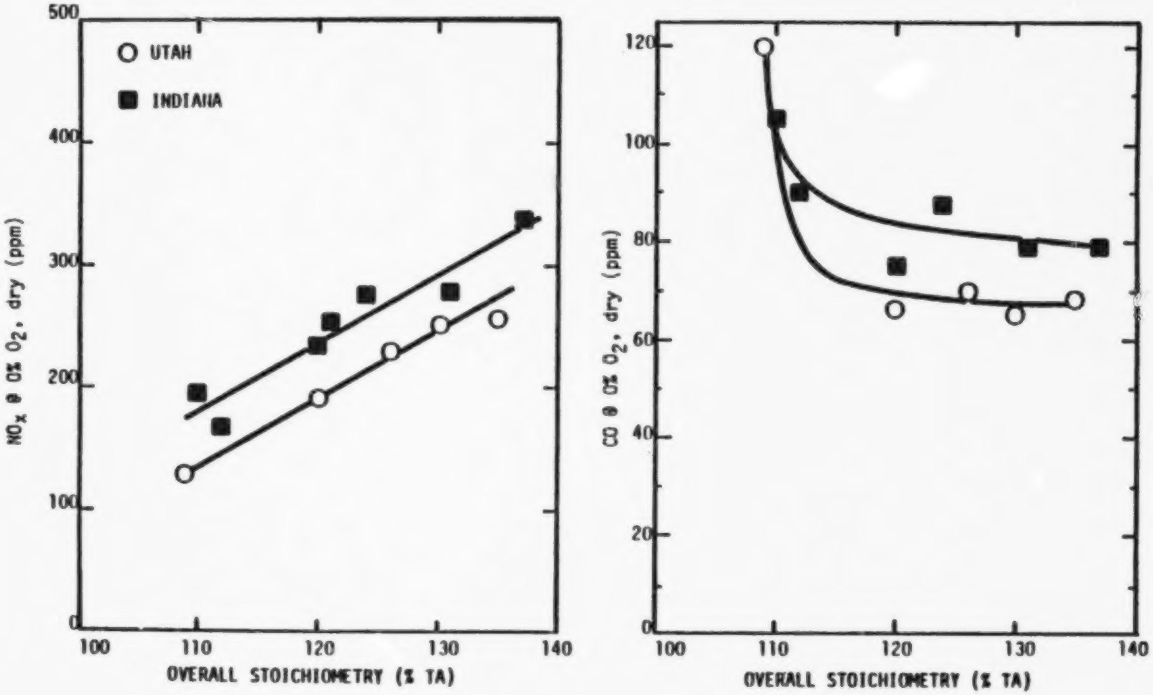


Figure 3-56. Comparison of excess air effect on emissions produced by the optimum short exit configuration with Utah and Indiana coals.

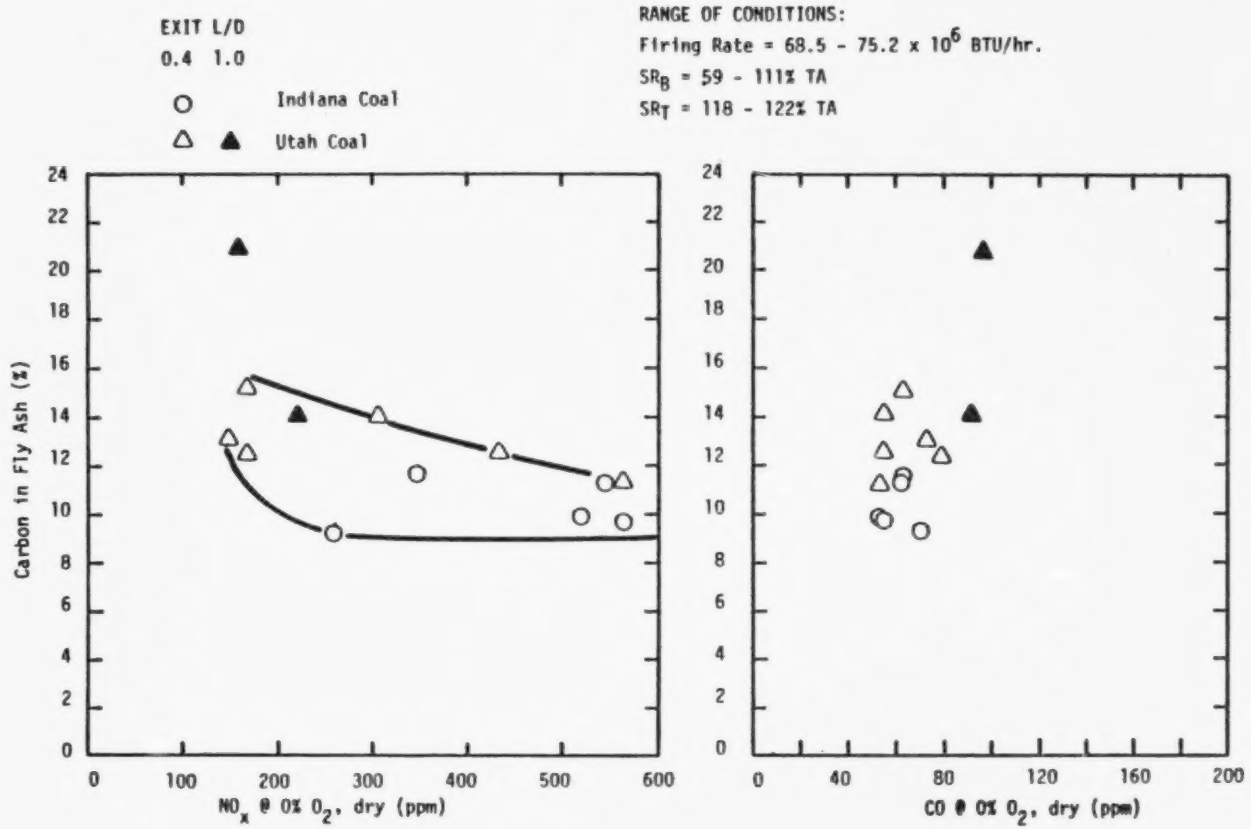


Figure 3-57. Range of fly ash carbon for final industrial prototype DMBs at optimum burner configuration.

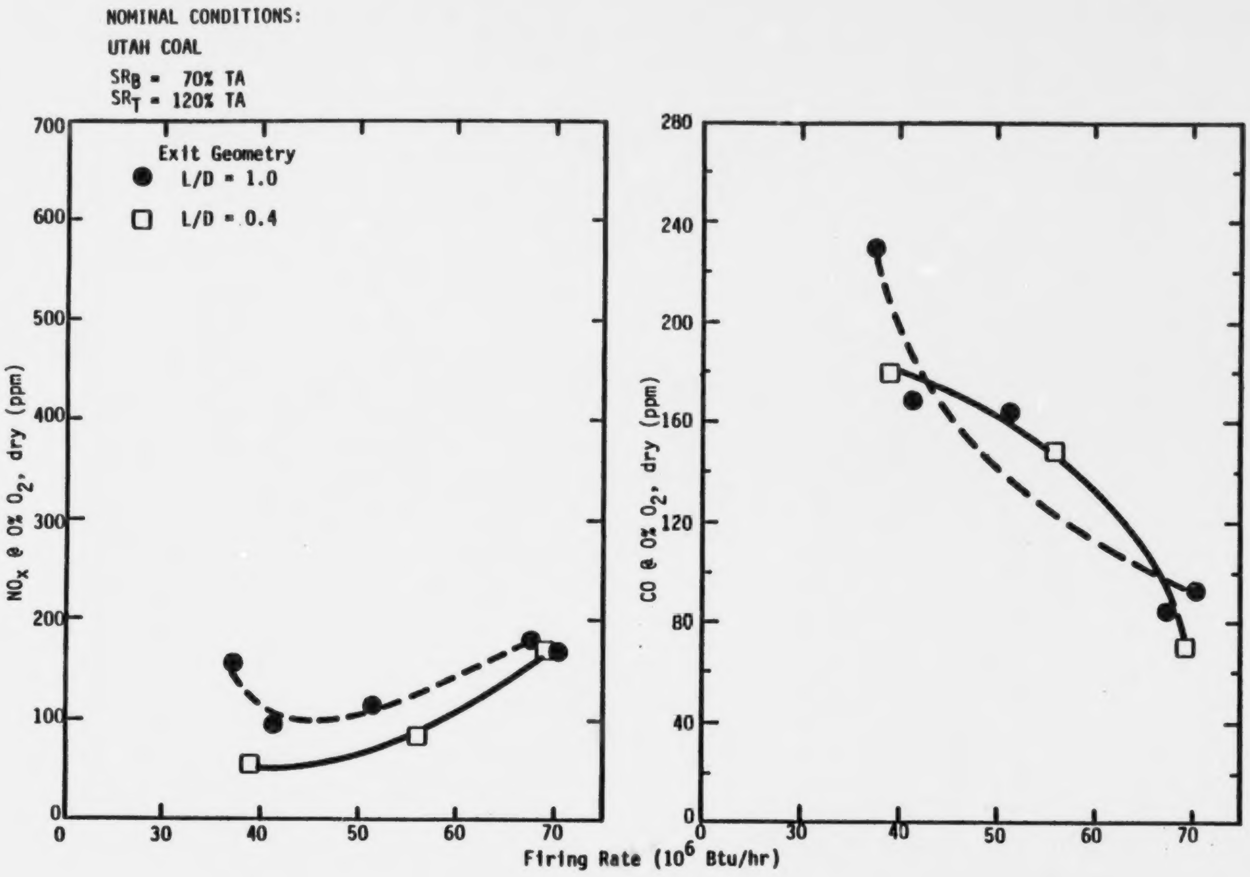


Figure 3-58. Effect of firing rate on final industrial prototype DMB performance.

Combustion efficiency, as indicated by CO emissions decreased with firing rate for both the short and long exit DMB configurations.

3.5.5 Parameters Related to Field Installations

Additional tests were conducted to evaluate the effects of parameters which may need to be adjusted to accommodate the practical aspects of DMB installation in full scale boilers including:

- Alternate tertiary air velocities
- Biasing tertiary air flow rates between ports
- Misalignment of burner components
- Coal fineness variations

The effect of tertiary air velocity on DMB performance was evaluated over a to 50-150 ft/sec range through the use of inserts. These inserts reduced the tertiary port diameters from a nominal 14-inches to 10 or 8 inches. Smaller ports would be desirable for field installations, since the smaller diameter ports would have a lesser impact on a boiler's structural integrity. Figure 3-59 summarizes the effect of tertiary velocity on burner performance. NO_x emissions were lowest with the two higher velocity ports, 10-inches and 8-inches in diameter. However, CO emissions were measurably higher for these port sizes, particularly at low burner zone stoichiometries. Thus, there is a trade-off between NO_x and CO emissions. The DMB design criteria result in minimum CO emissions at the expense of a slight NO_x emissions increase.

During these tertiary velocity tests, the effect of biased tertiary air distribution was evaluated. At WIPCO, a compromised arrangement of the tertiary air ports around the four burners was necessary, primarily due to structural considerations. The arrangement installed at WIPCO biases the tertiary air distribution to the top ports: i.e., more tertiary air is injected above the burners. For these new LWS tests, the tertiary air flowrate distribution to the top and bottom ports was varied. Stable flames could be maintained for the full range tested: 10-90 percent to the top two

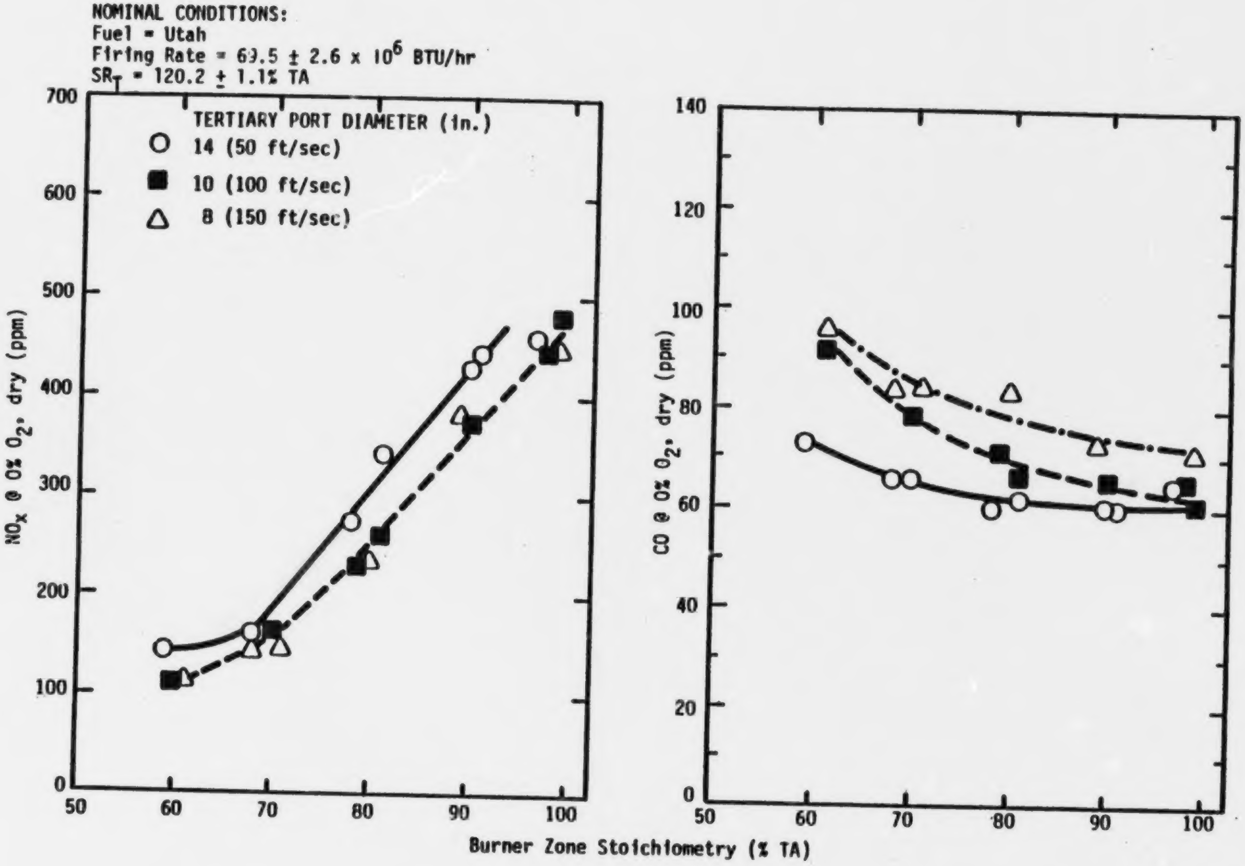


Figure 3-59. Effect of tertiary port velocity on short exit configuration performance.

ports. However, flame shape at the ignition point was marginal with nearly all the air added above the burners. Figure 3-60 summarizes the results of these tests. There was little effect on NO_x emission for the two high velocity cases. For the low tertiary velocity case NO_x emissions decreased by 30 ppm when the tertiary air was biased to the top ports. CO levels increased as the flow of tertiary air was biased to the top two ports. This suggests that the arrangement of tertiary air ports at WIPCO, with the large ports above the top row of burners, may not be conducive to efficient combustion with the DMBs.

The secondary air sleeves, which vary air distribution between registers are misaligned in the WIPCO DMB installation. The effects of sleeve misalignment were evaluated using the short exit DMB in an extreme configuration: the tops of both inner and outer sleeves open 100 percent while the bottoms of both sleeves were held closed. The potential effects of this misalignment were a change in the inner and outer secondary air flowrate distribution and a change in the distribution of air around the circumference of each annular secondary air passage. No impacts on burner performance we observed. During these tests the total secondary air flowrate was maintained constant independent of sleeve misalignment. However, in the field installation at WIPCO, the air distribution between burners and among the tertiary air ports was determined by the total restrictions in each burner passage. Thus, misalignment of some sleeves could have changed the restriction in those passages and altered the air flow rate distribution between burners for among the tertiary air ports. Also, the pressure drops across the sleeves were used to measure the air flow rates. Misalignment of the sleeves could have changed the calibrations. These impacts could not be evaluated during these new LWS tests.

The coal fineness for the majority of the LWS tests was consistently in the range of 80 percent through 200 mesh. To evaluate the effects of reduced fineness, the pulverizer classifier was adjusted to produce a fineness of about 65 percent through 200 mesh. With this coarser grind, large load swings and intermittent flame instability was observed. It is not clear whether these effects were due to problems in transporting the coarser coal

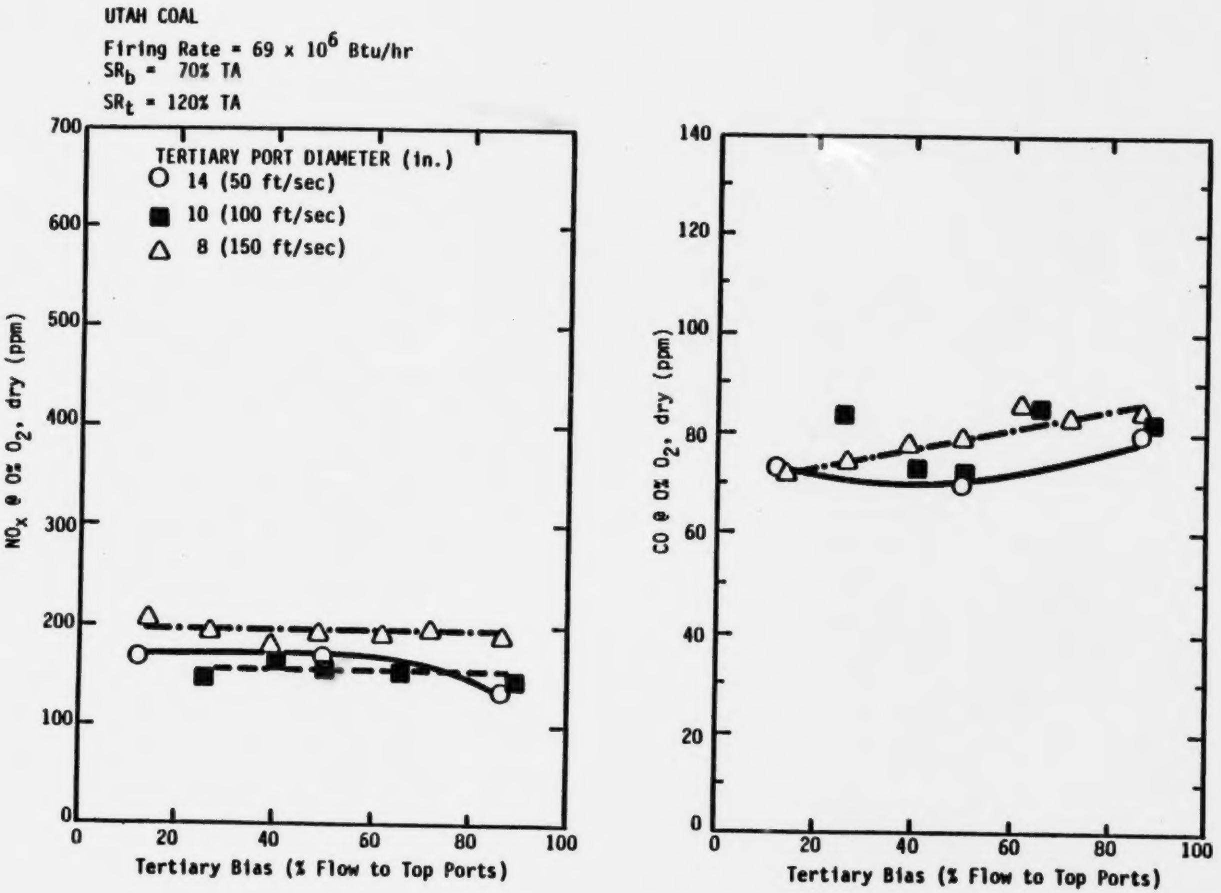


Figure 3-60. Effect of tertiary air bias on short exit burner performance.

particles to and through the burner or in the combustion performance of the burner. However, the results suggest that similar flame observations at WIPCO may have been due to coal fineness which was less than 65 percent through 200 mesh in many tests.

3.5.6 Comparison of Performance with Previous Prototype DMBs

The performance of both the long and short exit configurations of the final prototype DMB is compared with previous designs in Figure 3-61. NO_x emissions for the final two DMB configurations, both long and short exit designs, were similar and comparable to NO_x emissions from the DMB with FW parameters. The final two configurations could operate stabily down to an SR_B of 60 percent, while the DMB with FW parameters could achieve $SR_B = 70$ percent and the initial DMB on SR_B of 85 percent. However, the initial DMB, produced NO_x levels as low as the other designs at its minimum stable burner zone stoichiometry.

The short exit configuration of the final DMB produced the lowest CO levels and low CO even under deeply staged conditions. The CO levels were probably higher for the long exit design because of flame impingement on the cast refractory exit. The knee of the CO curves for the initial DMB and DMB with FW parameters occurred at higher burner zone stoichiometries.

Fly ash carbon content, another indication of combustion efficiency, was measured during tests of the DMB with Foster Wheeler parameters and the final DMB configurations. In general, the DMB with Foster Wheeler parameters had lower unburned carbon in the fly ash than did the final DMB designs, as shown in Figure 3-62. However, a wider operating range and a lower burner zone stoichiometries could be achieved by the final short exit DMB. Also, the degree of burnout achieved by the DMB with Foster Wheeler parameters was more sensitive to the level of staging than the final short exit configuration. The absolute levels of fly ash carbon, or burnout, are not necessarily representative of expected field operation. The relatively cold thermal environment and the bulk time-temperature history of the LWS fired at 70 x 10^6 Btu/hr may cause quenching of burnout reactions. Both designs

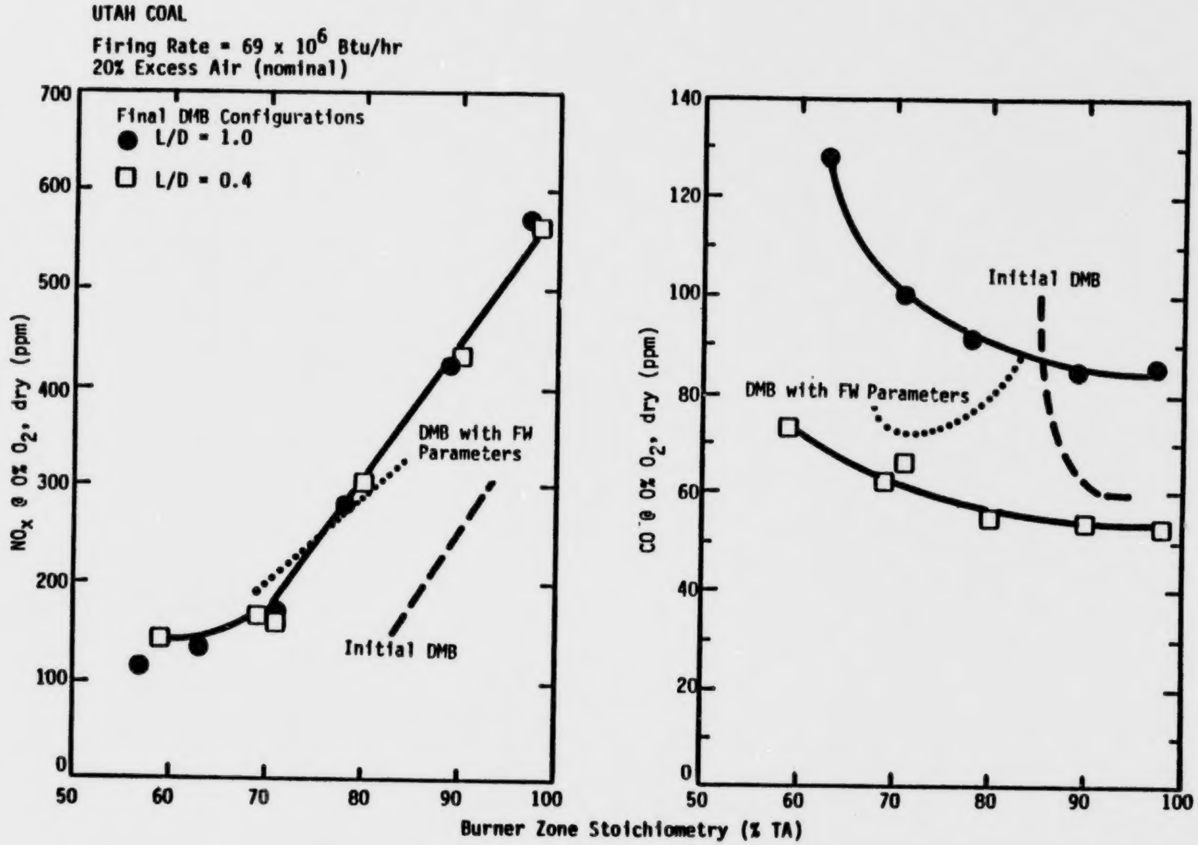


Figure 3-61. Comparison of burner performance with previous industrial prototype DMBs.

	DMB WITH FW PARAMETERS	FINAL DMB
FIRING RT(10^6BTU/hr	66.6 - 71.2	68.5 - 75.2
SR_B (% TA)	67 - 76	59 - 111
SR_T (% TA)	118 - 128	118 - 122

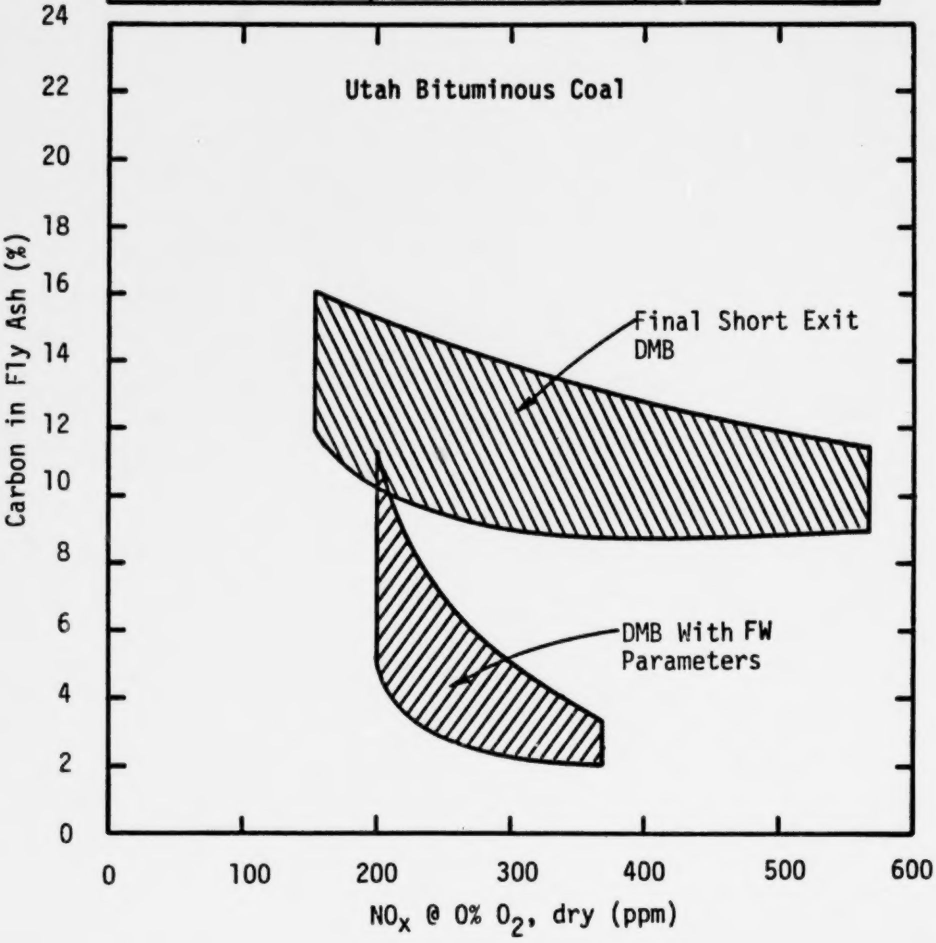


Figure 3-62. Comparison of fly ash carbon for prototype DMB designs.

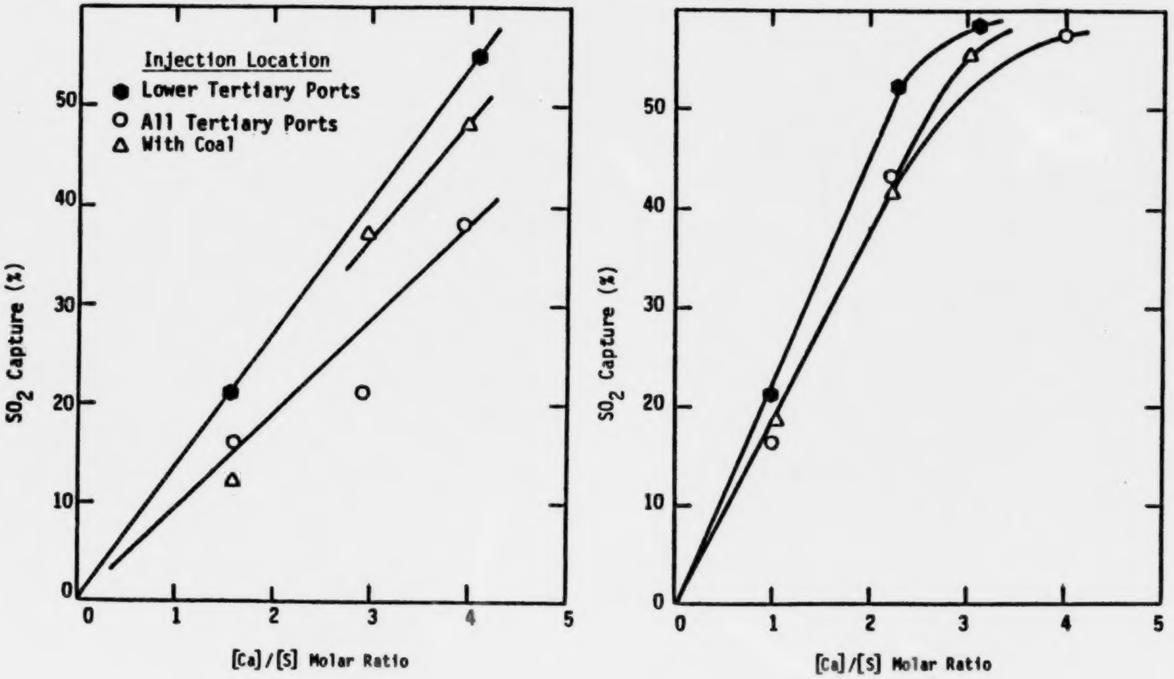
demonstrate that the DMB concept can be applied to Foster Wheeler hardware to produce low NO_x emissions with only slight impacts on efficiency.

3.6 SO_2 Reduction Potential of Industrial Prototype DMBs with Sorbent Injection

Sorbent injection tests were conducted to evaluate combined NO_x/SO_x reduction potential of the prototype DMBs. The DMB with Foster Wheeler parameters and the final prototype DMBs were both tested with sorbent injection in the new LWS. Sorbent tests were also conducted on the DMB with Foster Wheeler parameters in the MT. Two injection locations were studied: injection of sorbent into the coal stream and injection through nozzles located on the axis of each tertiary air port. The calcium-based sorbents used were Vicron 45-3, a high purity limestone ($CaCO_3$), and Colton hydrated lime [$Ca(OH)_2$]. The sorbent injection system and the characteristics of the sorbents are described in Appendixes B and C, respectively.

3.6.1 Sorbent Injection Tests For The DMB with Foster Wheeler Parameters

The initial sorbent injection tests using the DMB with Foster Wheeler parameters were conducted in the LWS using Vicron limestone as the sorbent. Sulfur capture results achieved with Utah and Indiana 2 coals are shown in Figure 3-63. Injection of limestone into the coal stream yielded slightly higher SO_2 reduction than injection through all four tertiary air ports for the Utah coal. Less of a difference in SO_2 capture for the two injection locations was measured for the Indiana coal. Higher SO_2 capture was achieved with the Indiana 2 coal which had 2.56 percent sulfur, compared to the Utah coal which had 0.87 percent sulfur. Figure 3-63 also shows that injection through the two lower tertiary air ports only resulted in higher SO_2 capture. Although not shown in Figure 3-63 similar tests with injection through the top ports only also resulted in higher SO_2 capture than injection. This was attributed to injection velocity. During the two port injection tests, the same sorbent/transport air ratio was employed, but the injector area was halved, resulting in higher injection velocities. The higher speed jets were characterized by significantly increased entrainment.



NOMINAL CONDITIONS:
Firing Rate - 70 x 10^6 BTU/hr
SR_B = 70% TA
SR_T = 120% TA

(a) Utah Coal

(b) Indiana 2 Coal

Figure 3-63. SO_2 reduction with injection of Vicron 45-3 for the DMB with Foster Wheeler parameters in the LWS.

For the tests of the DMB with Foster Wheeler parameters in the MT, it was necessary to reduce the firing rate to 54 x 10^6 Btu/hr as discussed previously. Experimental results from sorbent injection tests in the MT are compared with new LWS results in Figure 3-64. Prior to these tests, the Indiana 2 coal supply had been exhausted and a new supply from the same mine and seam was procured, designated as Indiana 3 (detailed analysis in Appendix B of Volume 2). This coal had a lower sulfur content than the original Indiana 1 and 2 coals (1.45 percent compared to 2.57 percent). Again, SO_2 capture was highest for Vicron limestone injected with the coal, while capture was significantly less when the sorbent was injected through the tertiary air ports. SO_2 reduction was similar when limestone was injected into the coal stream in both furnaces. However, SO_2 capture by sorbent injection through the tertiary air ports in the MT was lower than the reduction achieved in the new LWS. It was also observed that SO_2 capture increased with the higher sulfur Indiana coal. Thermal history is one of the key parameters controlling SO_2 capture. The high firing densities of the MT produced bulk gas temperatures up to 277°C (500°F) higher than produced in the new LWS, thus lowering SO_2 capture.

3.6.2 Sorbent Injection with the Final DMB Configurations

The SO_2 capture potential by the injection of sorbent material into the furnace through several passages of the prototype DMB was evaluated at the optimum operating point for the long exit configuration. Two processed, high purity materials were used; Vicron 45-3, a 97 percent pure $CaCO_3$, and 90 percent pure hydrated lime. The Vicron was injected into the coal stream and through nozzles located on the axis of each tertiary air port. Figure 3-65 summarizes the results of the sorbent injection tests. Injection of the hydrated lime through the tertiary ports yielded the highest capture, 60 percent at Ca/S = 2.0. Injection location had some effect on the SO_2 capture achieved with Vicron: 40 percent with coal injection and 35 percent with tertiary port injection both at Ca/S = 2.0.

The SO_2 capture potential of the short exit prototype DMB was evaluated using the same sorbents and injection locations used for the long exit

NOMINAL CONDITIONS:	LWS	MT
Firing Rate (10^6 Btu/hr)	70	54
SRB (% TA)	70	70
SRT (%TA)	120	120

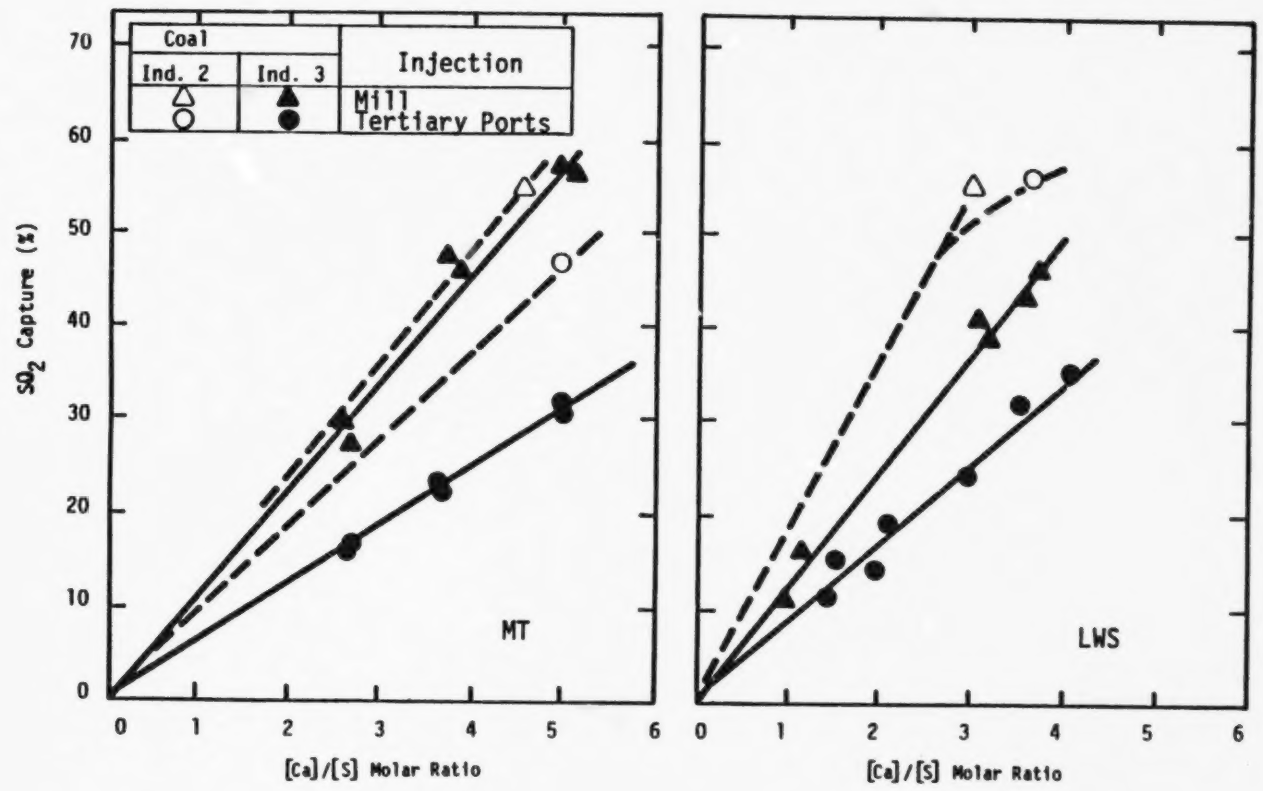


Figure 3-64. Sulfur capture with Vicron and the DMB with Foster Wheeler parameters in the MT.

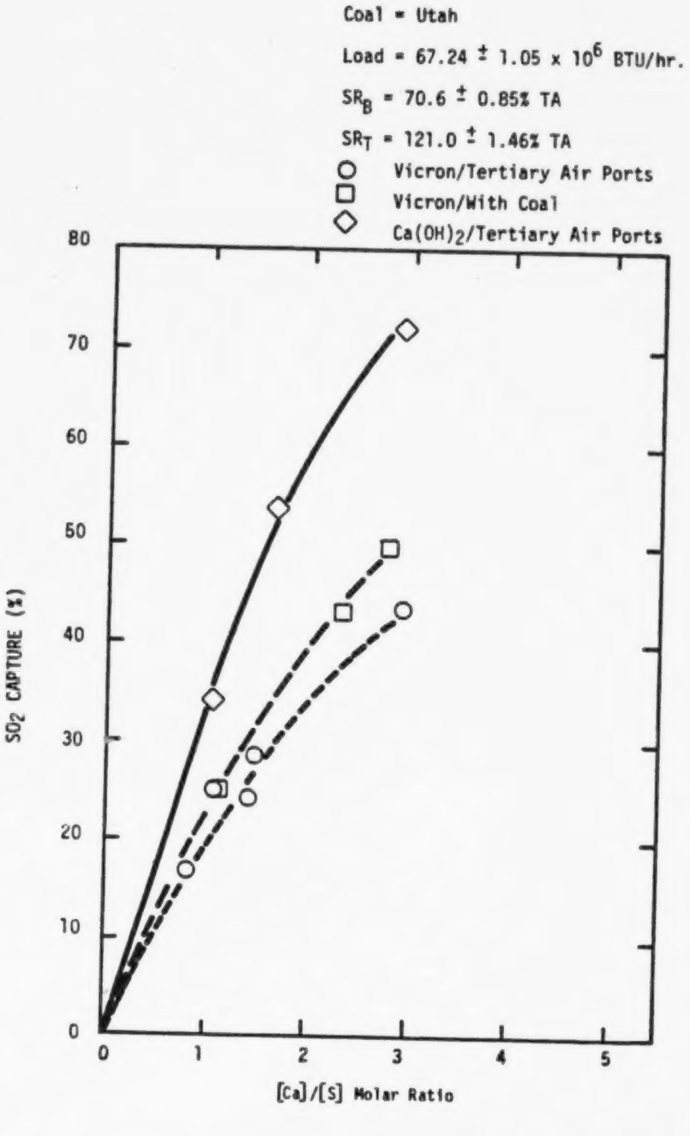
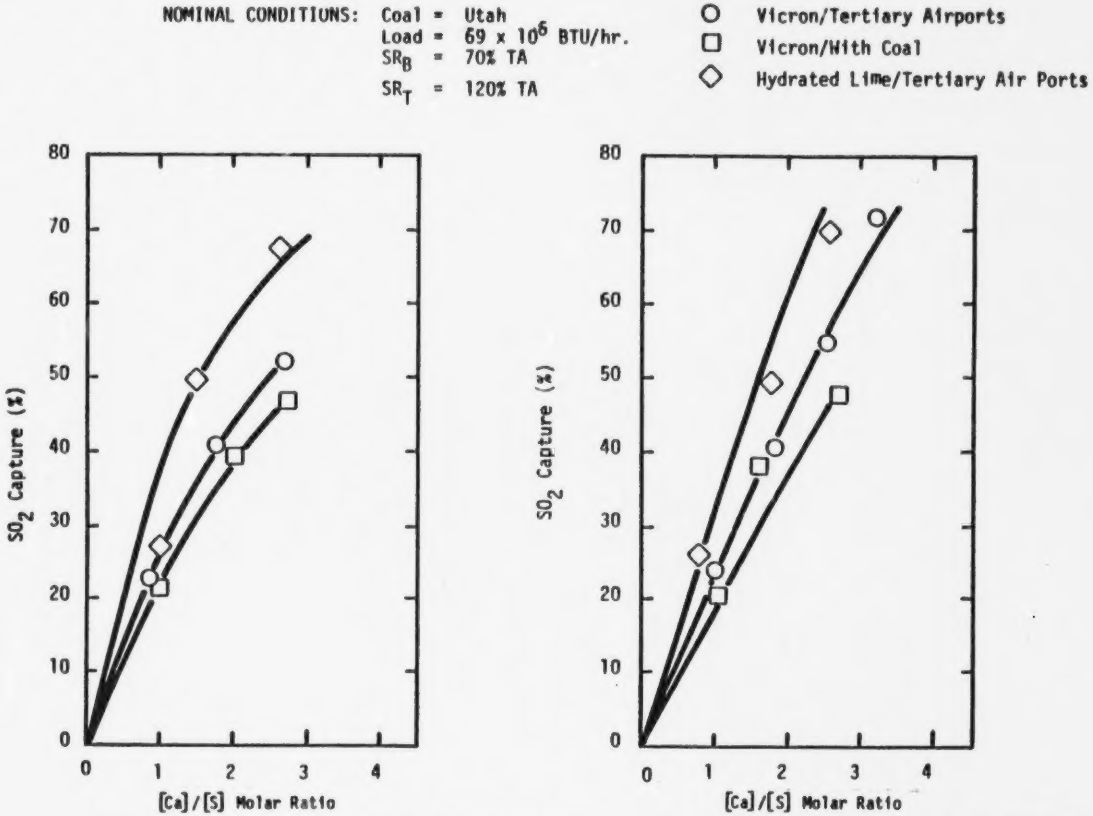


Figure 3-65. SO_2 capture achieved with the optimum long exit DMB configuration.

design. Figure 3-66 summarizes the results for tests with two different tertiary air velocities. Sulfur capture was similar for both cases. Hydrated lime, $Ca(OH)_2$, injected through the tertiaries yielded the highest SO_2 reduction, 57 percent at Ca/S = 2.0. Injection location had slight effect on the effectiveness of Vicron, with injection through the tertiaries giving 44 percent capture at Ca/S = 2.0 and 40 percent when injected into the coal stream. The level of SO_2 reduction achieved with the short exit design is compared to results with the long exit configuration in Figure 3-67. There was essentially no difference in capture for the two exit designs for limestone was added to the coal stream or for hydrated lime injected through the tertiary air ports. However, the short exit DMB achieved higher capture, for Vicron injected through the tertiary air ports than for the long exit DMB. Sorbent materials were also injected in tests with Indiana coal, the designated WIPCO baseline fuel. The Indiana coal has a higher sulfur content (1.46 percent, dry) than does the Utah coal (0.73 percent, dry). The effect of this fuel composition difference is shown for both Vicron and hydrated lime injection through the tertiary ports in Figure 3-68. The SO_2 reduction measured was higher for the higher sulfur Indiana coal, than for the Utah coal with Vicron. The differences were similar for the hydrated lime.

Results of the sorbent injection tests with both the long and short exit configurations of the final DMB design are compared with results from the DMB with Foster Wheeler parameters in Figure 3-69. Reduction of SO_2 with sorbent injection was significantly better with the two final DMB designs than for the DMB with Foster Wheeler parameters. Injection of limestone through tertiary ports yielded greater SO_2 capture than injection of the sorbent into the coal stream for the short exit final DMB, while injection with the coal was better for the other DMB designs.

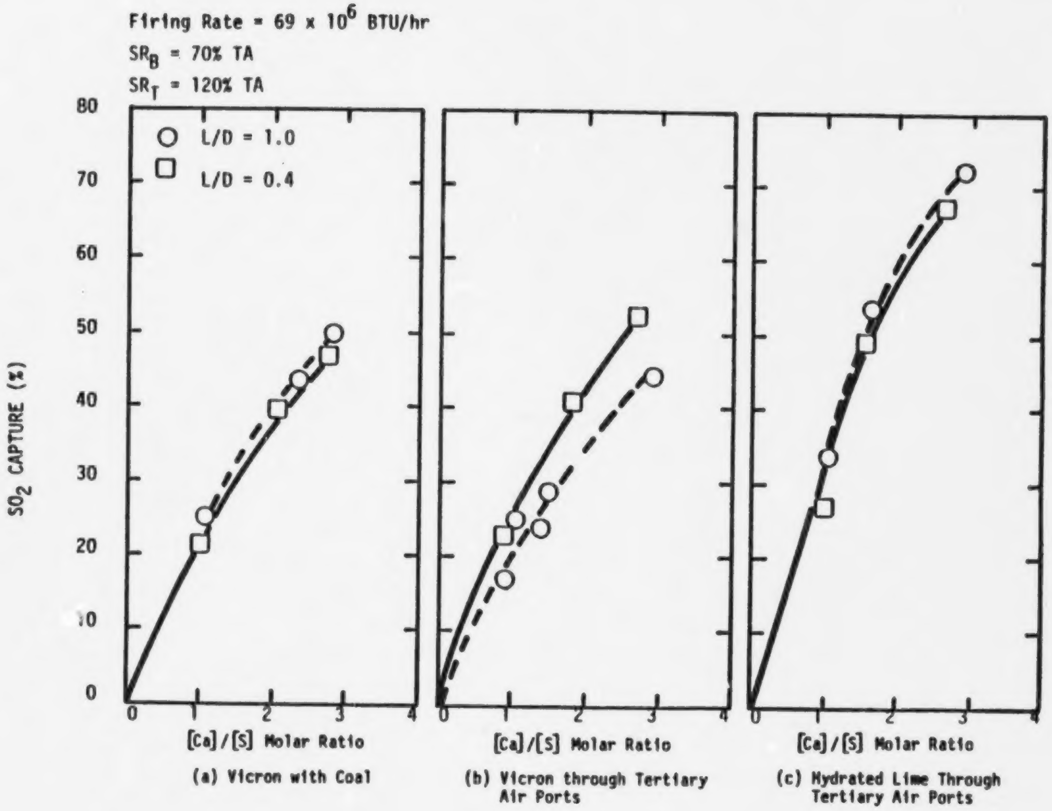
The difference in SO_2 reduction achieved by these different burner designs, injection, locations, fuel types and sorbent types suggests complex interactions. The interaction of the sorbent jet with the flame, peak flame temperature, and the effects on sorbent activation and calcination are still not well understood for large-scale systems. The large differences in SO_2 capture by dry sorbent injection among these prototype burners could



(a) Tertiary Air Velocity = 50 ft/sec.

(b) Tertiary Air Velocity = 100 ft/sec.

Figure 3-66. SO_2 capture potential with short exit configurations of final DMB.



(a) Vicron with Coal

(b) Vicron through Tertiary Air Ports

(c) Hydrated Lime Through Tertiary Air Ports

Figure 3-67. Effect of exit length on SO_2 capture with final DMB configurations.

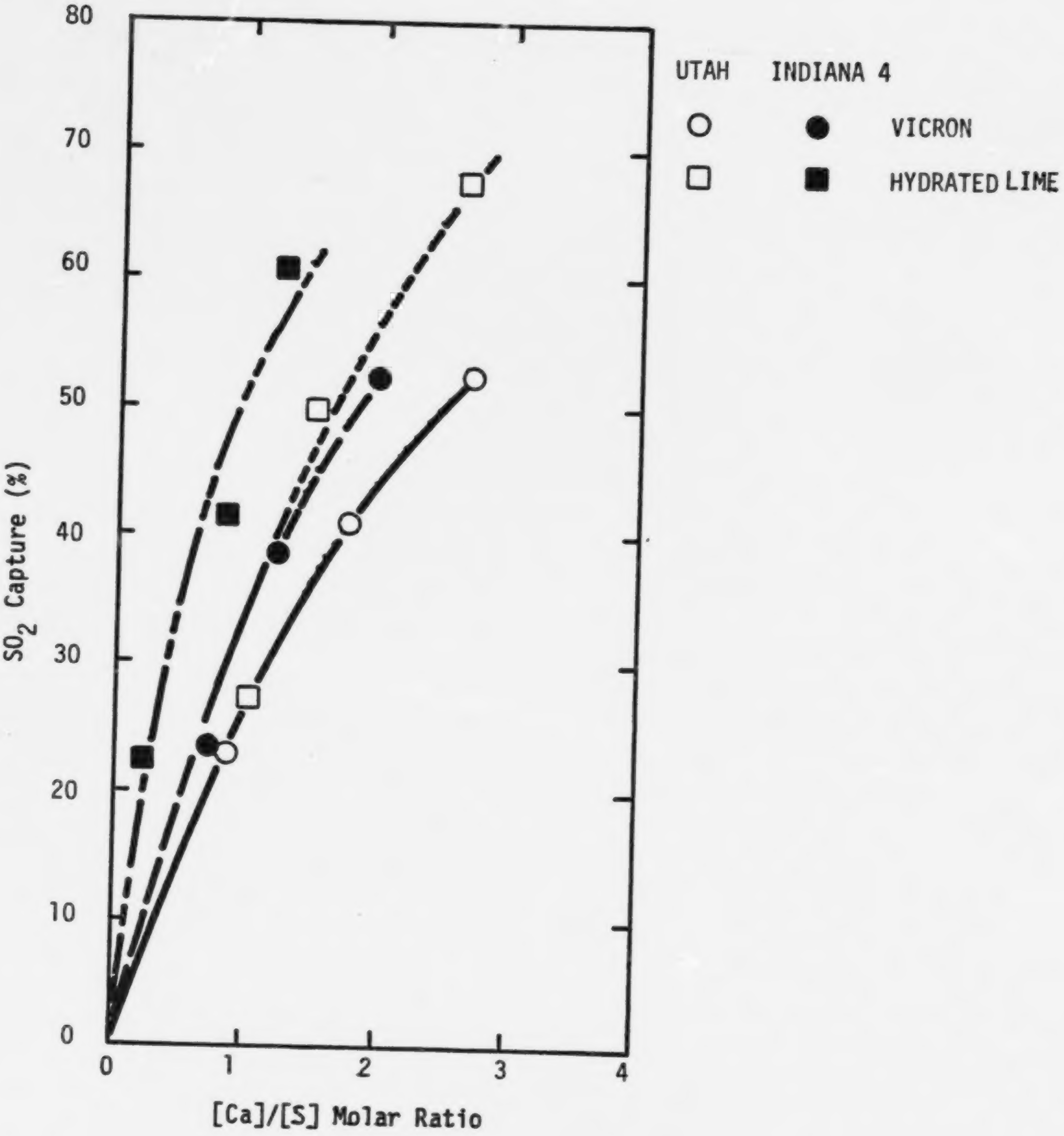
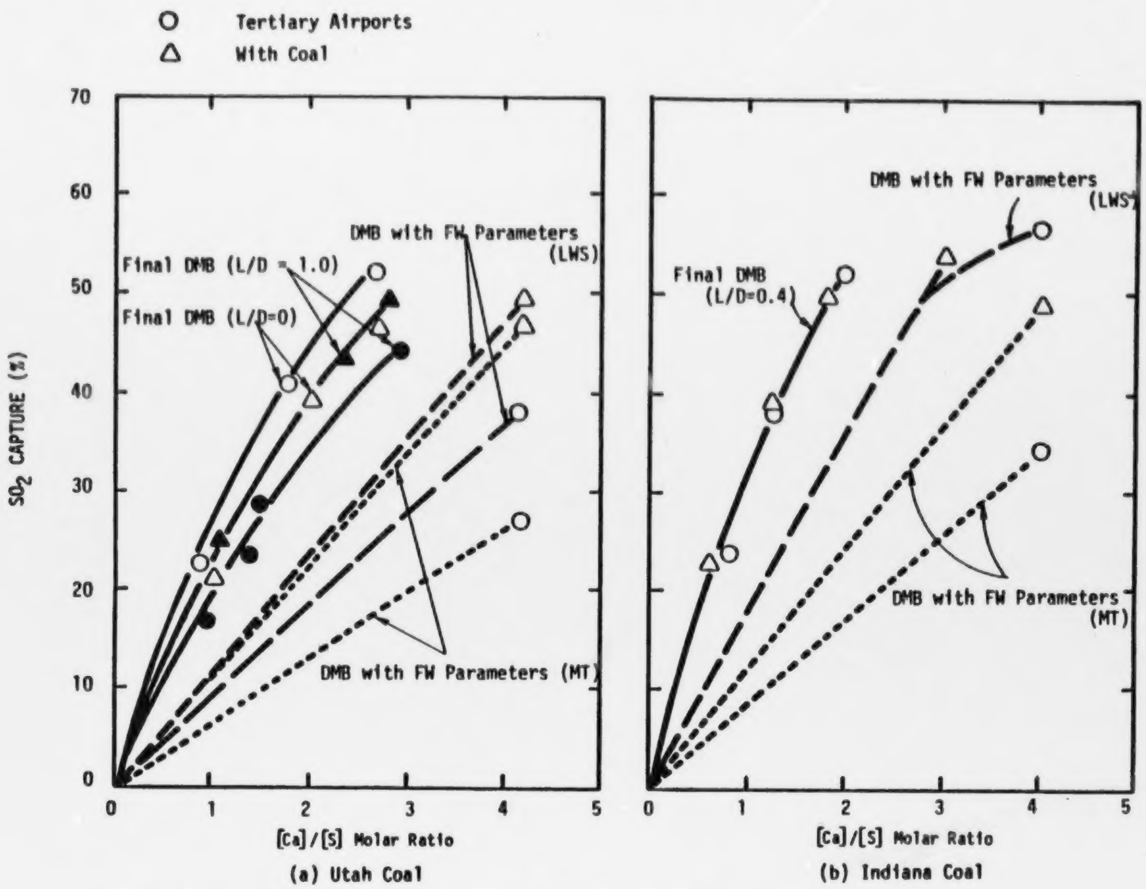


Figure 3-68. Effect of fuel composition of SO_2 reduction with sorbent injected through the tertiary air ports of the final DMB configuration.



(a) Utah Coal

(b) Indiana Coal

Figure 3-69. Summary of SO$_2$ capture using Vicron (CaCO$_3$) injection with industrial prototype DMBs.

therefore be related to the different mixing patterns and flame dynamics intrinsic with each burner design.

3.7 Tertiary Air Port Entrainment Study

The application of the DMB to multiple burner arrays requires that tertiary air ports be located between burners. For burner arrays where the burner to burner spacing is large compared with the tertiary air port spacing around each burner, each burner and its surrounding four ports would be expected to operate essentially independently. However, for burner arrays with small burner spacing, some interaction between the burners may occur.

The WIPCO DMB installation involved close burner spacing and tertiary air ports which were shared between the burners. Specifically, a single large port was located in the center of the four burner array. Smaller shared ports were mounted between the upper and lower burners outside of the array. The results of the field evaluation, presented in Section 4, have shown that it was difficult to adjust the array of four DMBs to achieve balanced conditions under low NO_x/high combustion efficiency conditions. Section 4.5 discusses several possible reasons for this behavior and it is concluded that the most probable explanation is non-uniform entrainment of tertiary air into the flames from the four burners.

Following the completion of the field evaluation, the entrainment of tertiary air from a port between four burners was evaluated using isothermal flow modeling techniques. The objectives were to:

1. Determine if the burner balancing problems experienced in the field could be attributed to non-uniform mixing of tertiary air into adjacent burner flames.

2. Evaluate potential design changes which would reduce the balance problems.

The following three subsections discuss the modeling approach, the test results and the implications for future DMB designs. In summary, these tests have shown that a tertiary air port located between adjacent burners will be uniformly entrained into the flames from both burners only if the burners themselves are carefully balanced. Even slight burner imbalance results in substantial entrainment of the tertiary air into the higher flow burner.

3.7.1 Modeling Approach

The fluid flow, heat transfer and chemical reaction processes responsible for entrainment of tertiary air into the flames from DMBs are too complex for precise analytical or experimental modeling. To provide a qualitative evaluation of the major parameters affecting entrainment, an isothermal flow modeling approach was used. This involved constructing a 1/10 scale model of the full scale DMBs and central tertiary air port at WIPCO and simulating the tertiary air flow and flames with ambient temperature air. Since all processes could not be simulated simultaneously, the model was constructed and operated primarily to simulate the factors influencing near field jet entrainment.

The best NO_x emission performance for the DMB occurs when the flame has a short standoff distance with the base of the flame within the burner exit. The near field entrainment characteristics of such a burner system are most closely simulated by geometric scaling and this approach was used for the small scale burners in this study. It should be noted that Thring-Newby scaling considerably expands the diameter of the burner and increases the near field entrainment. The design of the burner used in the isothermal tests is illustrated in Figure 3-70. It was scaled to approximately simulate the flow patterns produced by the full scale burners. It has a single secondary register to generate swirl which is a simplification over the dual registers in the full scale burner. The annular coal nozzle of the full scale burner was simulated by an axial stream of air flowing through an annular passage. Perforated plates were used to balance the air flows between the primary and secondary air passages simulating the full scale burner flow rates. Since the full scale burner incorporates Foster Wheeler's

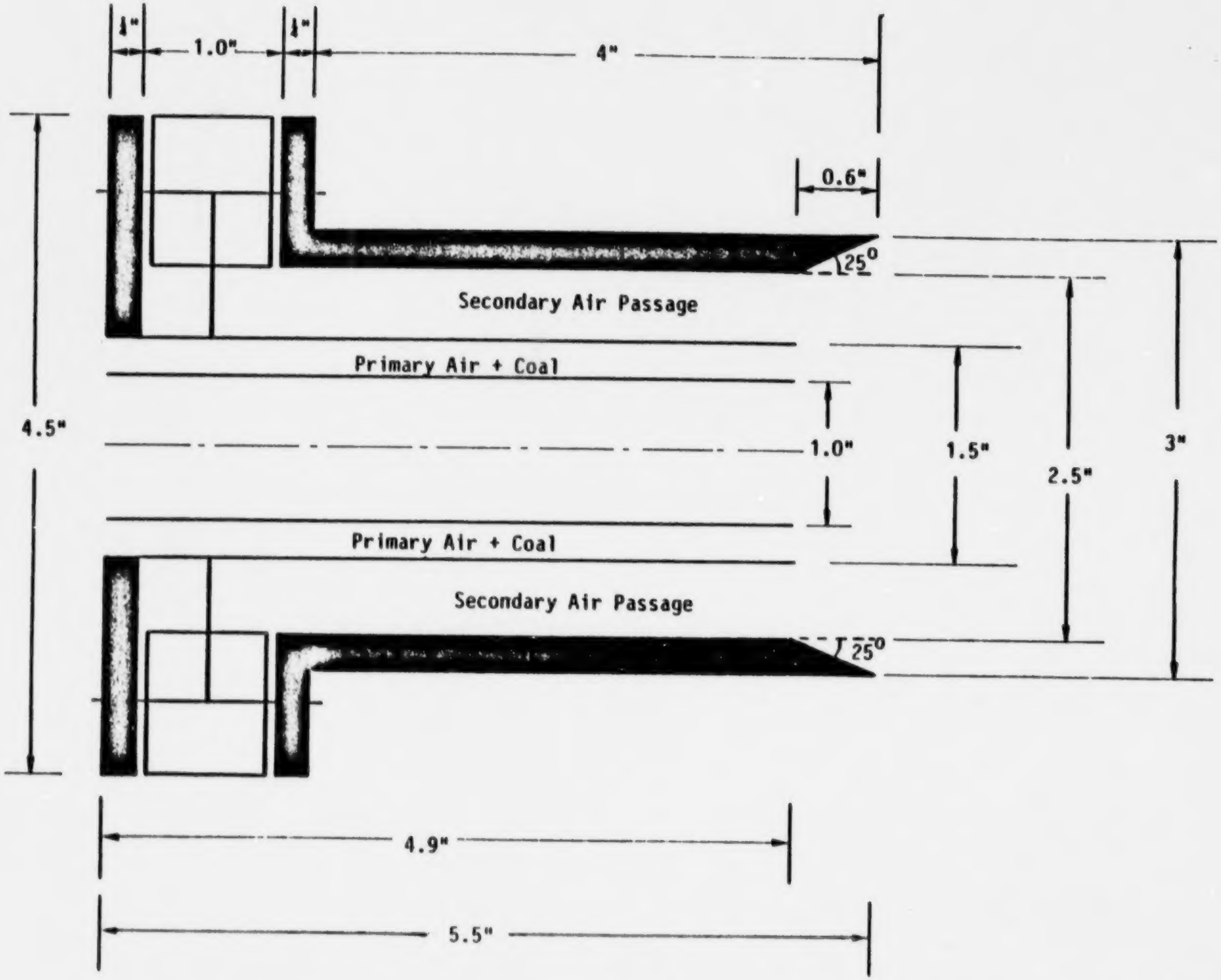

¼"
1.0"
¼"
4"
0.6"
25°
Secondary Air Passage
Primary Air + Coal
4.5"
1.0"
1.5"
2.5"
3"
Primary Air + Coal
Secondary Air Passage
25°
4.9"
5.5"

Figure 3-70. Isothermal flow study - burner design.

proprietary parameters, only the general features of the burner exit were simulated.

A different scaling approach was used to simulate the central tertiary air port. In the full scale burner system, the flow from the tertiary air port enters the furnace at about 600°F and mixes with the hot furnace gases which are at about 2400°F. Simple geometric scaling of the tertiary air port would result in an increase in the rate of entrainment due to the gas density difference. To account for this affect, the tertiary air port diameter was increased by the square root of the ratio of gas densities.

Four of the scale burners and the scaled tertiary air port were mounted on a test plate simulating the front wall of the WIPCO furnace as shown in Figure 3-71. The plate was then mounted in an enclosure simulating the rear and side walls of the WIPCO furnace.

3.7.2 Isothermal Test Results

The isothermal tests were conducted in three test series:

1. unconfined mixing tests
2. confined mixing tests
3. modified tertiary air port tests

For each test, the burner and tertiary air port flows were simulated with ambient temperature air. Flow patterns and tertiary air port entrainment were visualized by injecting smoke into the center tertiary air jet. The tests were conducted over a range of conditions centered on those simulating the operating conditions at WIPCO.

Unconfined Mixing Tests

The objective of these tests was to evaluate the interaction of the central tertiary air port with the surrounding four burners without the added complexity of the furnace wall enclosure. The test plate, illustrated in

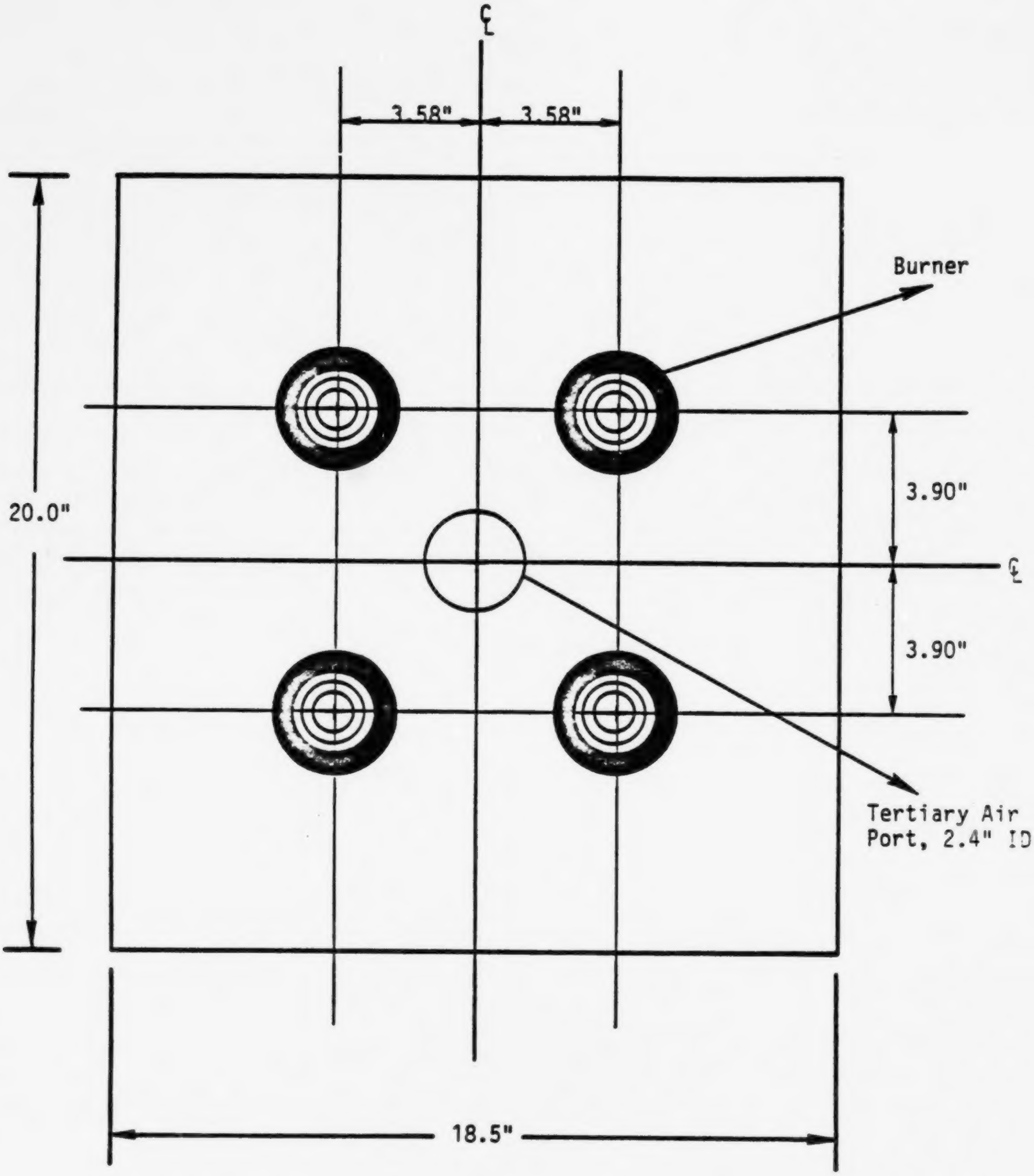

℄
3.58"
3.58"
Burner
20.0"
3.90"
℄
3.90"
Tertiary Air Port, 2.4" ID
18.5"

Figure 3-71. Isothermal flow study - burner and tertiary air port arrangement.

Figure 3-71, was mounted vertically with the flow moving upward. The air and smoke were captured in a fume hood suspended over the test apparatus. The burner and tertiary air ports flows were adjusted over a range of conditions and the furnace flow patterns were observed. Without side wall constraints, the burners entrained a considerable amount of ambient air. This made observation of the flow patterns difficult. Consequently, these tests were terminated and the second phase of testing in an enclosure was begun.

Constrained Mixing Tests

When the flow was enclosed by the simulated furnace walls, the flow patterns could be observed easily. This system was tested over the matrix of conditions listed in Table 3-11. The tests included balanced operation of all four burners over a range of conditions as well as swirl and/or flow imbalance to the burners. The results were as follows:

- Balanced Conditions - For balanced swirl and flow in all four burners, the central tertiary air port mixed fairly uniformly with all four burners. Under conditions where the jet was made "stiff" by increasing its momentum relative to that of the burners, the tertiary air jet tended to penetrate to the rear wall where it then mixed with the flames from the burners as shown in Figure 3-72. This is the mixing pattern which should produce balanced flows and low NO_X emissions in full scale DMB systems. For less "stiff" test conditions, the entrainment was more rapid and the jet tended to "wander" between the burners somewhat as illustrated in Figure 3-73. Under very low tertiary air momentum conditions, the jet was occasionally entrained into the base of the flames. These flow patterns would be expected to produce flames with characteristics varying with time and higher NO_X emissions since the tertiary air is mixed into the burner zone.

- Unbalanced Swirl - Unbalanced swirl in the four burners had little effect on the entrainment of the central tertiary air jet. Even substantial swirl differences such as no swirl on two of the

TABLE 3-11. ISOTHERMAL MODELING TEST MATRIX

Parameter	Value
Center Jet Momentum	Low Medium High
Swirl Intensity	30^o, 60^o Blade angle
Swirl Pattern	Co-swirl Counter-swirl
Burner Imbalance	Uniform Flow biased to one side
Port to Burner Spring	Standard Large

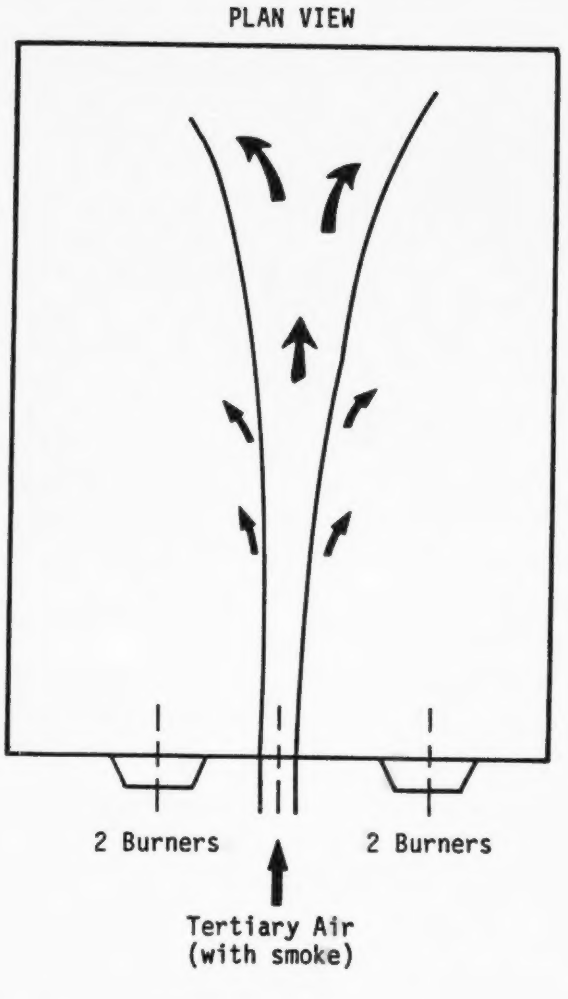

PLAN VIEW
2 Burners
2 Burners
Tertiary Air
(with smoke)

Figure 3-72. Center tertiary air jet mixing - balanced burners, high momentum teritiary air.

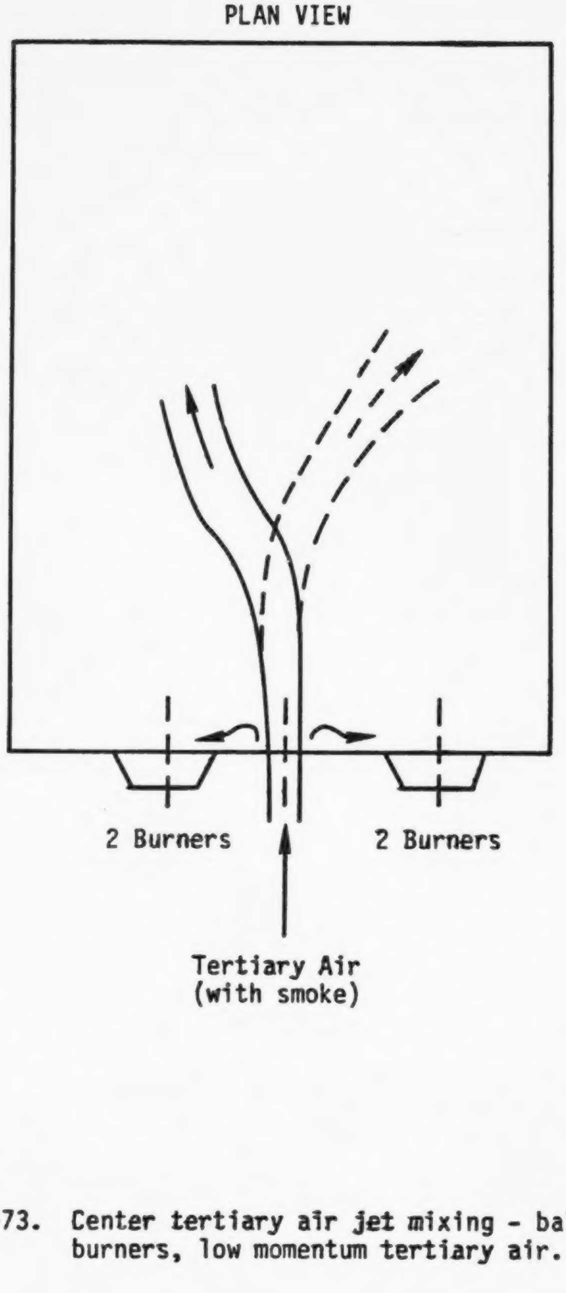

PLAN VIEW
2 Burners
2 Burners
Tertiary Air
(with smoke)

Figure 3-73. Center tertiary air jet mixing - balanced burners, low momentum tertiary air.

burners and 60^{o} swirl on the others produced no significant non-uniform tertiary air port mixing.

- Unbalanced Burner Flow - Unbalanced burner flow produced significant non-uniform entrainment of the tertiary air jet. The tertiary air jet was always entrained into the burner(s) with the higher flow rates. The effect was very pronounced as illustrated in Figure 3-74 especially for lateral (left right) imbalance. Essentially all of the tertiary air was entrained into the higher velocity flow even for slight (25 percent) burner flow imbalance. The result was strong circulation patterns in the furnace enclosure as illustrated in Figure 3-74. The degree of entrainment was reduced somewhat by increasing the tertiary jet momentum but this was a small effect compared to the major imbalance produced. Non-uniform swirl in conjunction with non-uniform flow had little effect on the non-uniform entrainment.

These results suggest that it should be difficult to balance DMBs with shared tertiary air ports. Any differences in flows to the burners would be greatly accentuated by the non-uniform entrainment of the tertiary air. In addition, in fired systems, the entrainment characteristics of the flames would be influenced by the entrainment of the tertiary air flow. The flames with substantial entrained tertiary air would tend to be hotter and entrained more tertiary air. Thus, any perturbations which tended to increase the "entrainment power" of one flame would result in preferential entrainment of air from a shared tertiary air port. For substoichiometric DMB flames, this would increase the flame temperature further increasing its entrainment power. This would lead to a "latching" effect where flow perturbations in an otherwise balanced system would cause non-uniform entrainment patterns to be established.

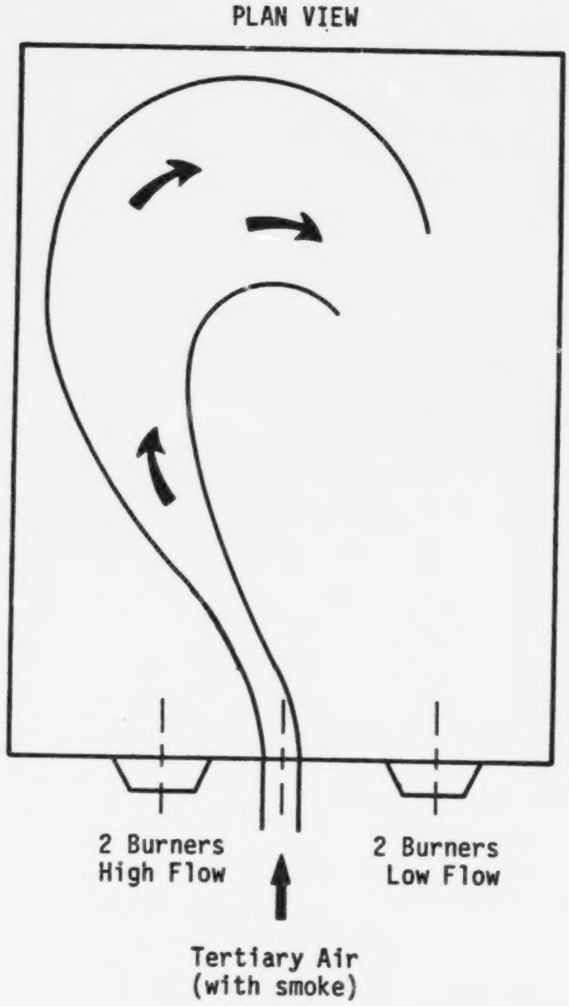

PLAN VIEW
2 Burners
High Flow
2 Burners
Low Flow
Tertiary Air
(with smoke)

Figure 3-74. Center teritiary air jet mixing - unbalanced burner flow.

Modified Tertiary Air Port Tests

Additional tests were conducted to evaluate potential methods of reducing the flow imbalance problems. The following modified tertiary air port designs were tested:

1. Replacing the single central tertiary air port with for ports, one for each burner.

2. Same as above but with each of the four tertiary air ports angled towards its adjacent burner.

3. A single tertiary air port with swirl.

Unfortunately, none of these approaches restored the flow imbalance. Dividing the tertiary air ports into four separate jets makes each jet less "stiff" and more easily entrained into the flow from the burners. Thus, this approach made the system more sensitive to burner flow imbalance. Angling the four ports slightly towards the burners improved the flow distribution somewhat but the tertiary air was entrained closer to the base of the flame which would increase NO_x emissions in a full scale system. In addition, for burner imbalance on the order of 25 percent, even the four angled tertiary air jets were immediately entrained into the higher velocity burner flow. Swirl on the tertiary air jet increased its rate of mixing and increased the flame imbalance problems.

3.7.3 Implications

These isothermal tests provide a qualitative indication of the flow and mixing patterns only. Nevertheless, the results suggest that the burner balancing problems experienced in the full scale field evaluation could be due to the in-furnace mixing problem. The only approach tested which tended to reduce the non-uniform entrainment significantly was increasing the tertiary air port momentum. Based on these results, future DMB installations should avoid tertiary air port between closely spaced burner as much as possible. If the DMB must be applied to closely spaced burner arrays, it may be desirable to increase the tertiary air velocity to reduce imbalance problems. In addition, the burner controls should be designed for improved control of burner air flow rates compared to the WIPCO installation.

4.0 DMB FIELD EVALUATION

This section presents the design of the DMBs retrofit to the host boiler and the results of the field evaluation. The DMB installation is discussed in Subsection 4.1. The installation was completed in August 1981 and the unit was returned to commercial operation. A brief series of checkout tests were conducted by Foster Wheeler to ensure that the burners could be operated with the tertiary air ports closed prior to the NO_x optimization tests with the tertiary air ports open. These checkout tests are discussed in Subsection 4.2. Following these tests, the unit was operated by the station personnel for 14 months pending availability of EPA funding. The NO_x optimization tests began in November 1982 and continued through March 1984. Over this period, a number of short and long term tests were conducted under DMB operating conditions (tertiary air ports open). The remainder of this section discusses these tests and results. The test approach and procedures are presented in Subsection 4.3. The effect of the operating variables and optimum settings are discussed in Subsections 4.4 and 4.5 respectively. These tests were conducted under controlled conditions established by test personnel. They were brief, averaging only a few hours per test. Additional tests were conducted over longer time periods with the unit under the control of the plant personnel. These extended term tests are discussed in Subsection 4.6. Throughout the test program, boiler performance and tube wastage were monitored. The results are presented in Subsections 4.7 and 4.8 respectively.

4.1 DMB Installation at Pearl Station

The DMBs installed at Pearl Station were designed to meet the DMB design criteria to the maximum extend possible. However some comprises in both the DMB's and boiler design parameters were designed as summarized as below:

- Central Portion of the Burner

  The burners installed at Pearl Station were identical to the prototype DMB with Foster Wheeler parameters except for the materials of construction which were upgraded to meet the requirement for continuous operation. The comprises with the respect to the DMB design criteria were discussed in Section 3.

- Tertiary Airport Locations

  The burner spacing and structional design of the Pearl Station boiler could not accommodate the desired tertiary airport arrangement. Considerably changes in both the number and location of the tertiary airports were required.

- Tertiary Airport Design

  Alternate designs for the tertiary airport dampers were selected.

- Control System

  The burner management system was replaced with a modern system which included electric drives where the tertiary airport dampers and registers on each burner.

- Windbox

  A new windbox was installed.

- Structural Considerations

  New structural members were required to support the hoppers.

It should be noted that the modifications required to install the DMBs in the Pearl Station boiler are highly site specific and are not necessarily representative of the modifications which would be required in other installations. The DMB is intended primarily for new installations. In new installations, the application of the DMB is greatly simplified since provision for its design requirements can be made prior to boiler construction.

The retrofit installation at Pearl Station commenced during the normal schedule Spring outage in April, 1981 and was expected to require five weeks. Prior to the installation, Foster Wheeler had designed the retrofit components based on drawings of the boiler and original burner management system. During the installation it was determined that these drawings did not reflect the actual wiring of the original burner management system. This required redesigning the circuitry and rewiring the new burner management system. This and several other problems extended the time required for the equipment modification substantial. The modifcations were completed and the unit was returned to service in August, 1981. It should be noted that these problems were not related to the DMB design. Subsequent DMB installations could be completed without these complications.

The remainder of this subsection details the design and equipment modifications for the DMBs installed at Pearl Station.

4.1.1 Burner Design

Figure 4-1 shows the general arrangement of the DMBs installed at Pearl Station in this program. The burner exit geometry is only appoximate (the specific exit design parameters are proprietary to Foster Wheeler). These burners were designed to meet as many of the DMB design parameters as possible and still enable the burner array to function safely within the existing boiler furnace. Peak temperature levels, temperature differentials, thermal expansion, and radient heat transfer from the furnace were considered.

The retrofit DMB's employed as much of the current Foster Wheeler commercial design standards as possible. Those standards determined the detailed design of the core air pipe, coal nozzle, exit goemetry, and the secondary air flow and swirl controls. There is no indication that the inherent design differences or performance parameters of a DMB impact any of

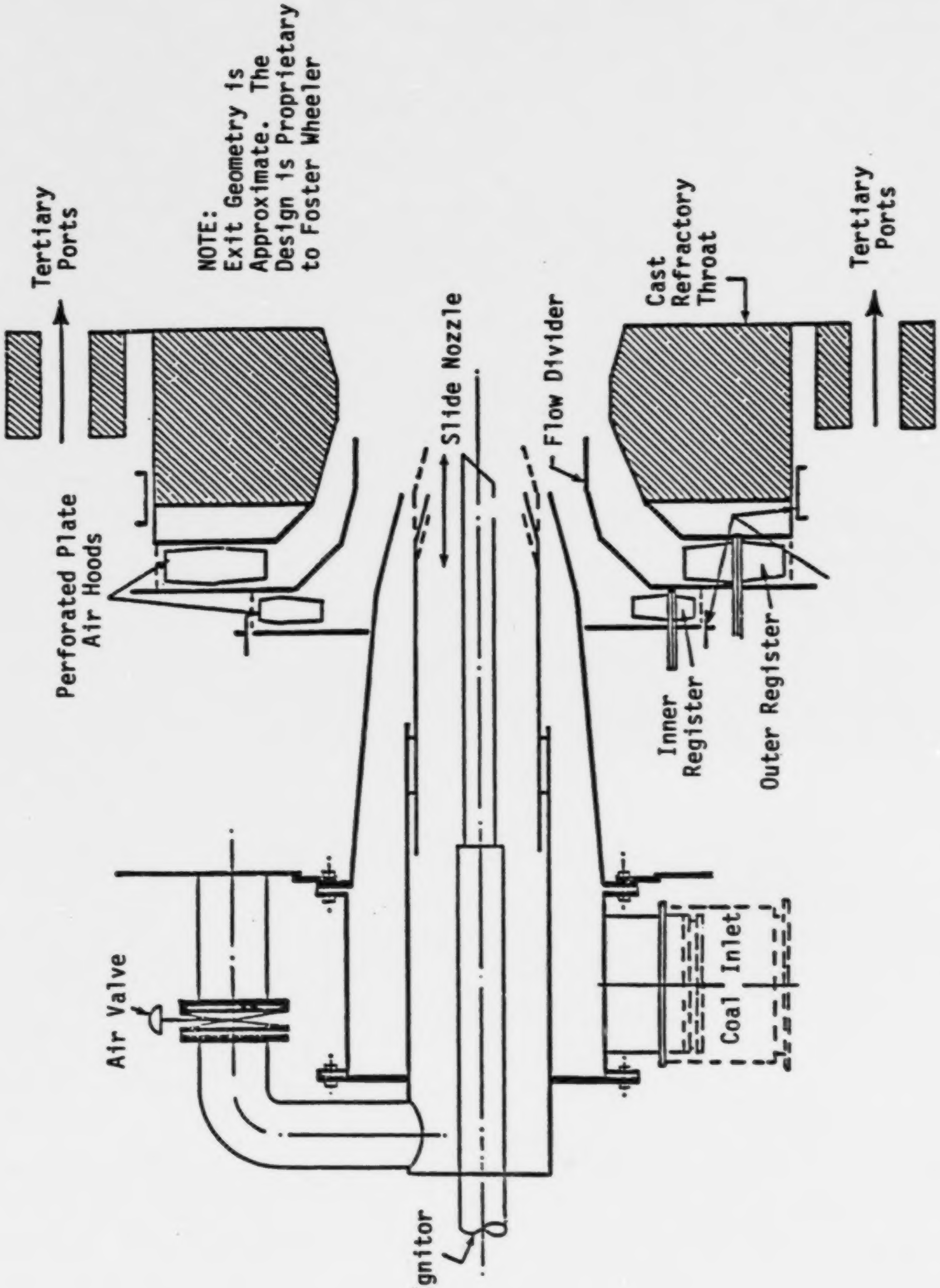

NOTE:
Exit Geometry is Approximate. The Design is Proprietary to Foster Wheeler
Tertiary Ports
Tertiary Ports
Cast Refractory Throat
Slide Nozzle
Flow Divider
Perforated Plate Air Hoods
Inner Register
Outer Register
Air Valve
Coal Inlet
Ignitor

Figure 4-1. Pearl Station DMB.

these conventional burner design considerations. A wide variety of internal burner components (fuel injectors, registers, etc.) can be utilized and still generally satisfy the DMB design parameters.

4.1.2 Tertiary Air Port Locations

The WIPCO unit could not accommodate the desired tertiary air port arrangement illustrated in Figure 4-2. This arrangement produced the 50 ft/sec DMB design criteria velocity through each port with a mass flow distribution equivalent to having each burner surrounded by four separate ports. For example, the port in the center had four times the area of the corner ports since it contributed to four burners. For tests of the prototype DMB and the prototype DMB with Foster Wheeler parameters in the old and new LWS, four tertiary air ports were arrayed around the burner with the same spacing as the array in Figure 4-1. However, all four ports were 12.0 in. diameter.

This tertiary air port arrangement would have distributed the air uniformly around each burner at the velocity specified by the DMB design criteria with a minimum number of ports. However, applying this array to the WIPCO unit caused the following structural problems:

- Interference with buck stays
- Interference with windbox trusses
- Interference with pulverizer air supply ducts
- Elimination of hopper support tubes

The WIPCO unit was designed with buck stays between, above and below the burners. Installation of the tertiary air ports in the desired array would have interfered with all three buck stays. The windbox front face the outboard portion of the burners were supported by several trusses in the windbox. The tertiary air ports are control mechanisms would have interfered with several trusses. The two bottom corner tertiary air ports were directly over the pulverizer air supply ducts. Control systems for the ports would have interfered with air flow to the pulverizers. Finally, the additional

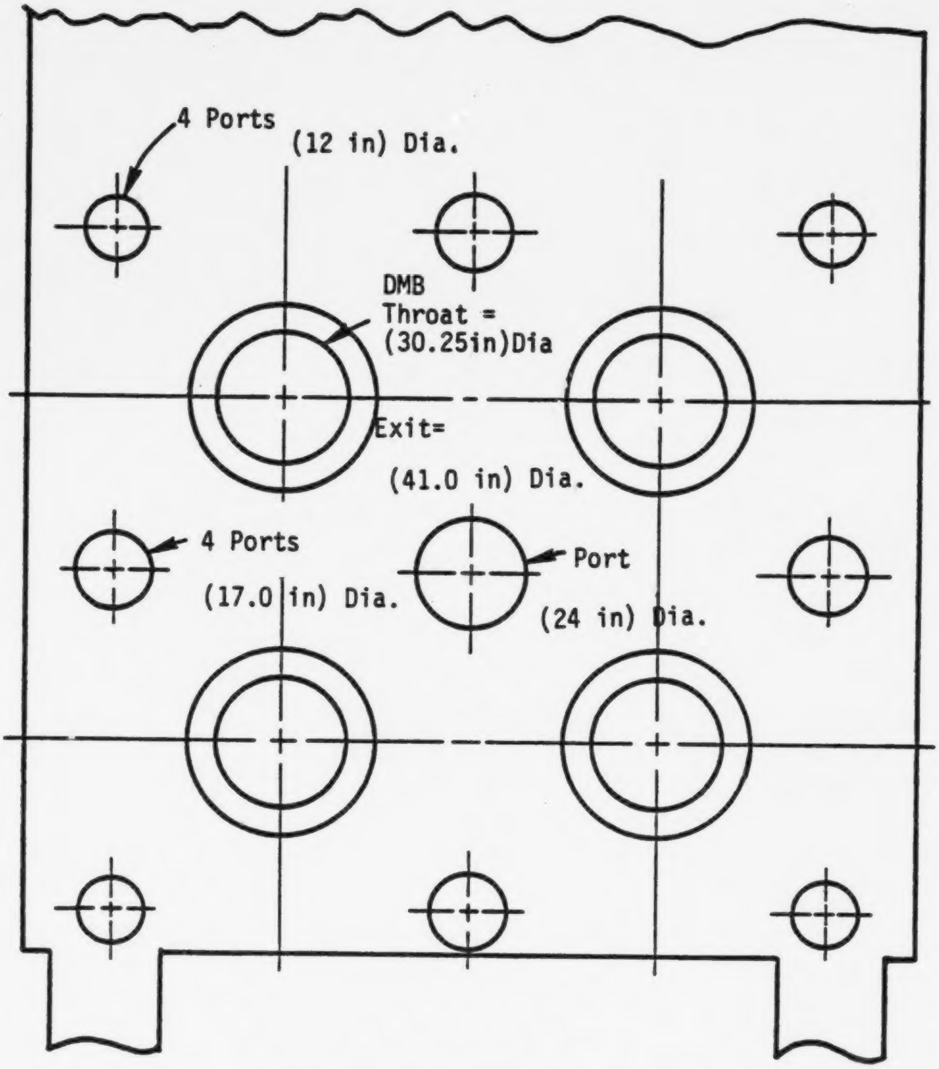

4 Ports
(12 in) Dia.
DMB
Throat =
(30.25in)Dia
Exit=
(41.0 in) Dia.
4 Ports
(17.0 in) Dia.
Port
(24 in) Dia.

Figure 4-2. Desired DMB arrangement.

tube bends required for the tertiary air ports would have affected almost all of the remaining straight tubes in the front face which normally support the hopper.

After considerable analysis and discussions by EER, EPA and Foster Wheeler, the compromise tertiary air port arrangement illustrated in Figure 4-3 was selected. This arrangement distributes the tertiary air around and between the burners while minimizing structural problems. The total open area for the 13-tertiary air ports is about 9 percent less than for the desired port arrangement. This results in a slight increase in tertiary air port velocity. The tertiary ports above the burners are the maximum size that will clear the buck stay. The port in the center was reduced in diameter to allow clearance for its control mechanism between the burner registers. The ports along the sides have been moved to allow free flow into the pulverizer ducts. The bottom of the windbox is lowered to provide a plenum for installation of the lower tertiary air ports.

The structural problems which could not be eliminated by this tertiary air port arrangement are as follows:

- Front Wall Replacement - Due to the large number of complex tube bend the entire front wall had to be replaced.

- Buck Stay Removal - The buck stay between the burners had to be removed and additional windbox structures were constructed to hand the pressure loads.

- External Hopper Support - The front wall strength was inadequate to support the hopper due to the large number of tube bends. An external hopper support was constructed to handle the hopper weight.

These retrofit problems are a result of the existing boiler design which did not account for the possibility of tertiary air port installation. If

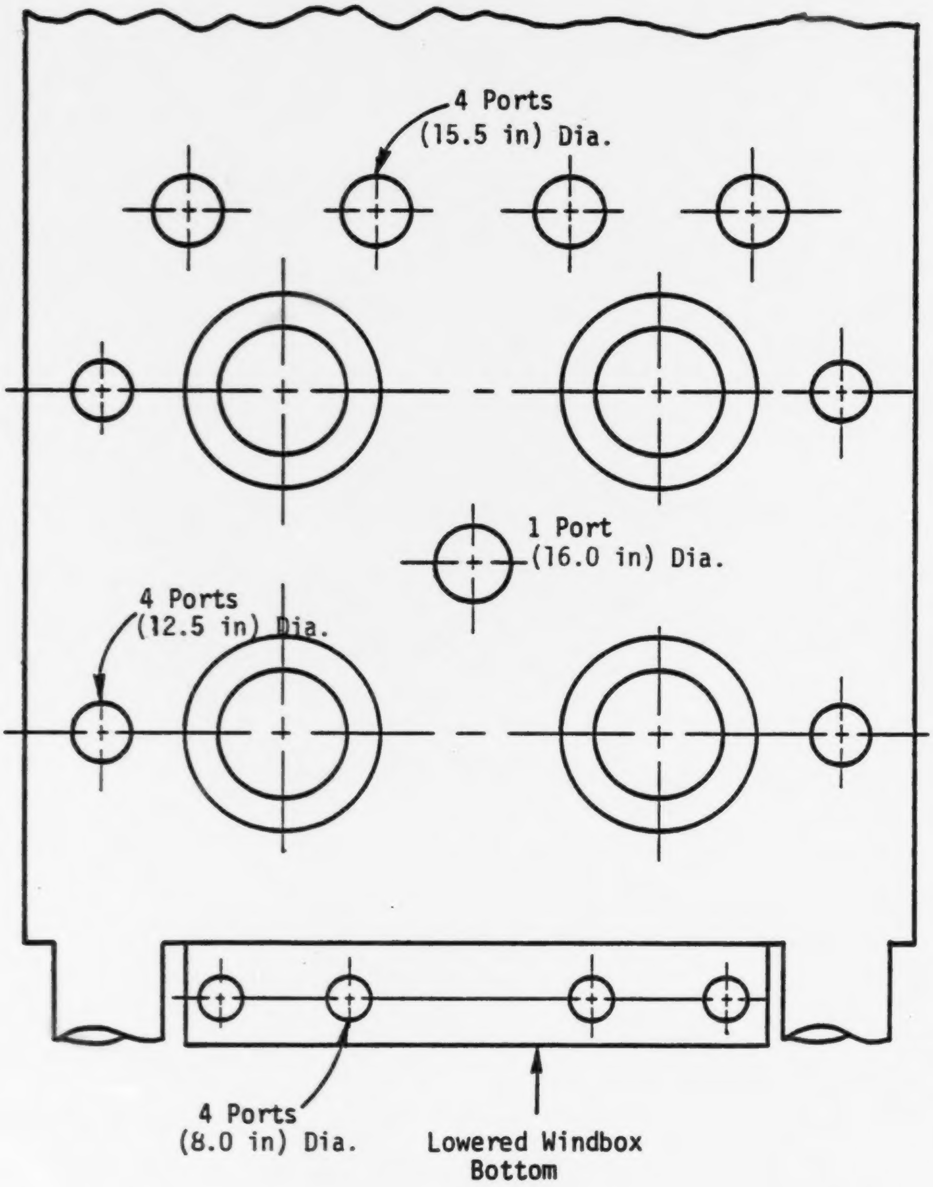

4 Ports
(15.5 in) Dia.
1 Port
(16.0 in) Dia.
4 Ports
(12.5 in) Dia.
4 Ports
(8.0 in) Dia.
Lowered Windbox
Bottom

Figure 4-3. Final compromise port arrangement.

the DMBs were installed on a new unit, a more optimum tertiary air port array could be accommodated by judicious design of the boiler structure.

4.1.3 Tertiary Air Port Design

The control of air flow to the ports can be accomplished in a number of ways. Again, similar to many of the internal burner components, a unique design for the control element is not part of the DMB design parameters. Any design that permits regulation of the flow through the tertiary ports over the burner load range will be adequate. Mechanical considerations are similar to those mentioned for the burner design, largely a function of the thermal environment. Two control damper designs were utilized at Pearl Station. The first, shown in Figure 4-4, provided individual control for all but the lowest four ports. The flow to those ports was controlled simultaneously by the second design, illustrated in Figure 4-5.

The cylindrical damper shown in Figure 4-4 operated similar to a bunsen burner. The tertiary air port was lined with four inches of refractory. The air passed through four holes in the refractory equipped with preforated plates. "A rotating can" with four holes matching those in the preforated was assembled over the central structure. As the can was rotated, the holes in the can and refractory could be aligned to maximize air flow. Alternately, the holes could be rotated so as to maximize restriction. This provided for variably air flow. The damper was designed with generous clearances so that considerably leakage air passed through the dampers even in the closed position. It should be noted that the refractory lining and damper mechanism required considerably more space than indicated by the tertiary port opening itself. This was a key factor in selecting the tertiary air port locations.

The alternate tertiary air port shown in Figure 4-5 was a convenient way of controlling the air flow to the four lowest tertiary air ports. These ports were located in an extension to the windbox between the primary air ducts as was illustrated in Figure 4-3. Air passed from the main windbox into the extension through a rectangle passage covered with a perforated plate. A sliding gate damper located over perforated plate could be moved to

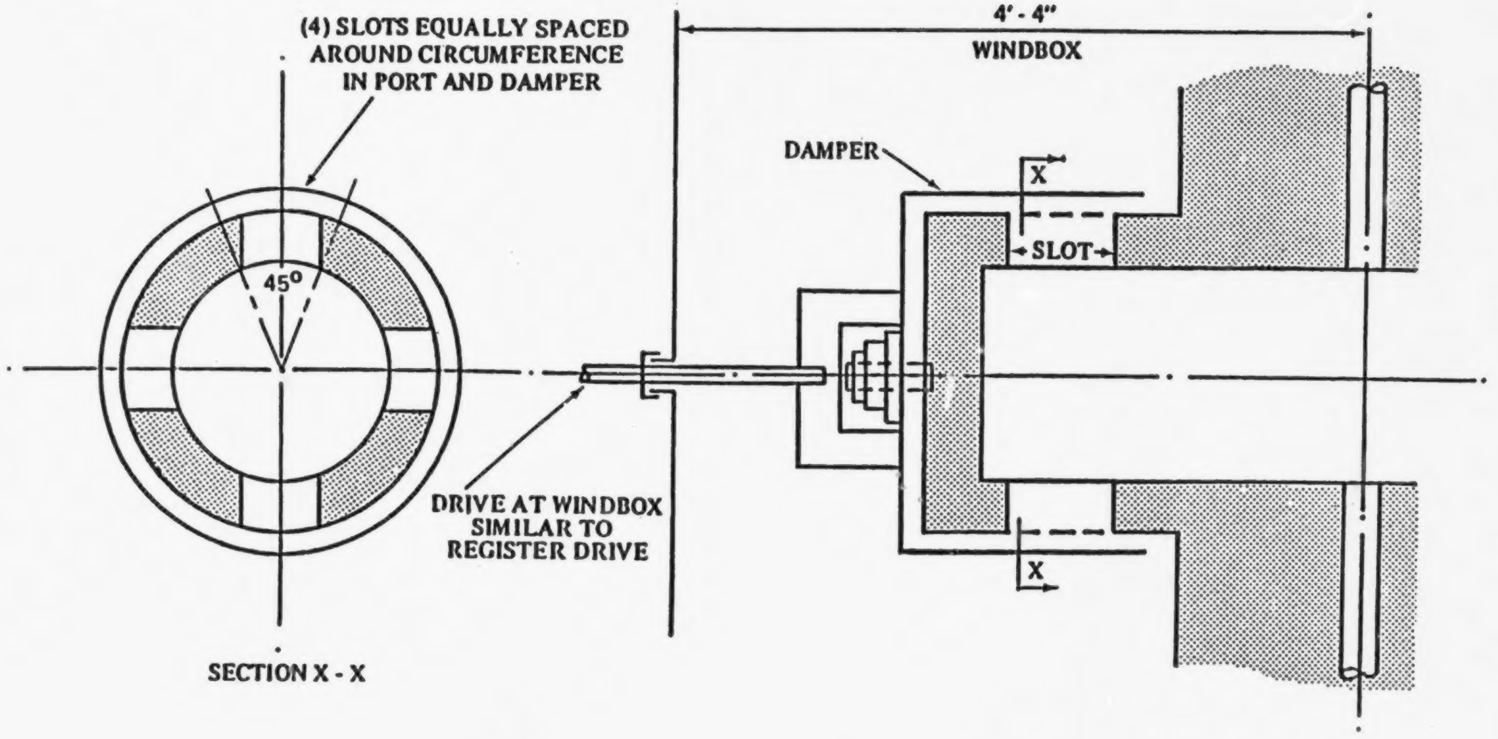

(4) SLOTS EQUALLY SPACED AROUND CIRCUMFERENCE IN PORT AND DAMPER
45°
SECTION X - X
DRIVE AT WINDBOX SIMILAR TO REGISTER DRIVE
4'-4"
WINDBOX
DAMPER
X
SLOT
X

Figure 4-4. Cylindrical-tertiary port damper design.

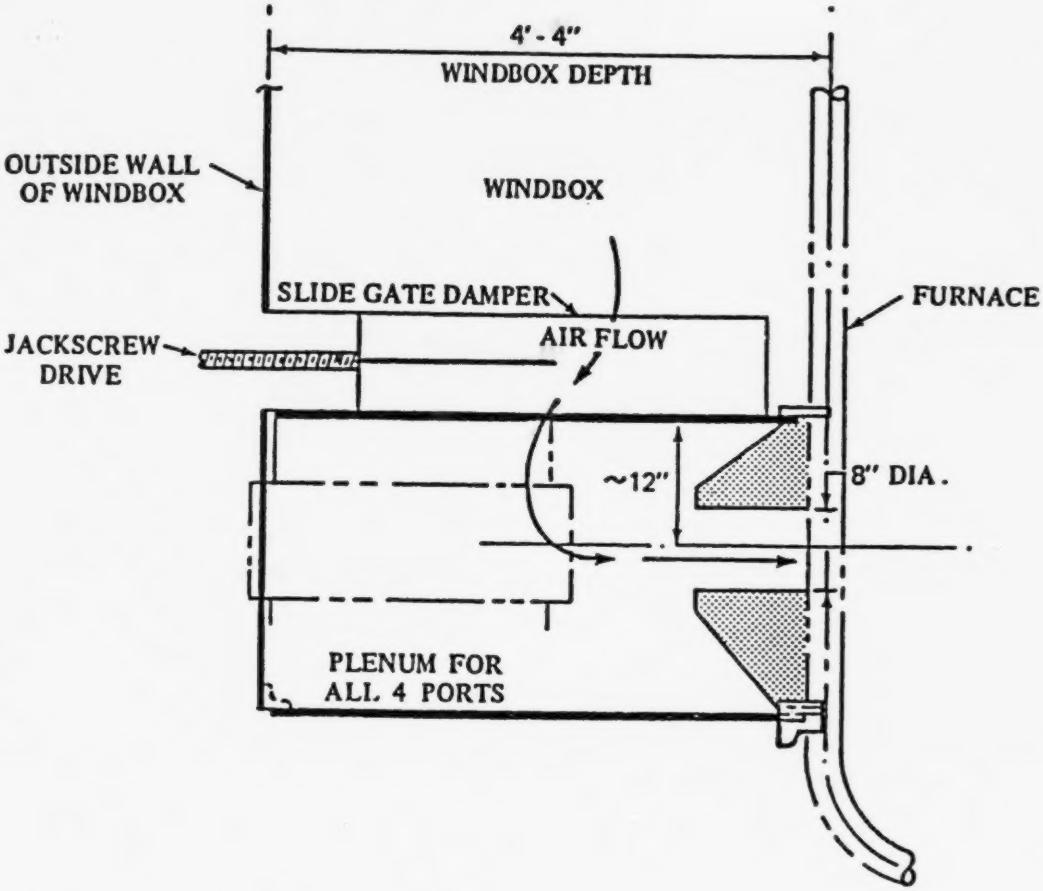

4'-4"
WINDBOX DEPTH
OUTSIDE WALL OF WINDBOX
WINDBOX
SLIDE GATE DAMPER
FURNACE
JACKSCREW DRIVE
AIR FLOW
~12"
8" DIA.
PLENUM FOR ALL 4 PORTS

Figure 4-5. Tertiary port damper design for lower ports.

vary the open area. This damper design could be shut almost air tight. However, to avoid over heating, the damper was never closed fully.

The flow rate of air through the tertiary air ports is critical since it establishes the burner zone stoichiometry. Consequently, each tertiary air port damper was equipped with pressure taps on each side of the control element. The air flow rate through each port was calibrated as a function of the measured pressure drop and damper position. The results of the calibrations are presented in Appendix D of Volume 2.

4.1.4 Control System

The burner management system for the intervane burners originally installed at Pearl Station were inadequate for the DMBs. The flame scanners were ultraviolet and often provided a loss-of-flame indication when the flame position varied even though the flames were stable. The original installation of eight adjustable controls: 1 register and 1 core air valve for each of the four burners. All controls were manual and were adjusted by the boiler operators from the firing floor. The adjustable controls for the DMB retrofited installation are listed in Table 4-1. There were a total of 34 adjustable controls. Sixteen of the controls were intended to be adjusted during the optimization test only and would normally be left in fixed positions for all unit operating conditions. These controls included the coal nozzles, inner and outer sleeves and core air valves. In the retrofit installation, they were equipped with manual lengthage drives and controls which could be adjusted by the operators from the firing floor. The other eighteen controls operated the inner and outer registers and tertiary air ports. Normally these controls would be adjusted by the operaters during normal unit operational changes including ignition and load changes or to achieve variations in the degree of stagings. In the retrofit installation, these eighteen controls were equipped with electric registered drives which were coupled to an electronic control system. These controls could be adjusted to any sitting from the control room or the firing floor. Limit switches were provided for automatic control of the registers to three

TABLE 4-1. DMB CONTROLS AT PEARL STATION

CONTROL	PARAMETER ADJUSTED	NUMBER OF CONTROLS	ADJUSTMENT FREQUENCY	CONTROL MECHANISM
COAL NOZZLE	PRIMARY VELOCITY	1/BURNER x 4 = 4	OPTIMIZATION TESTS	MANUAL DRIVES
INNER SLEEVES	INNVER SECONDARY VELOCITY	1/BURNER x 4 = 4		
OUTER SLEEVES	OUTER SECONDARY VELOCITY	1/BURNER x 4 = 4		
CORE VALVES	CORE AIR FLOWRATE	1/BURNER x 4 = 4		
INNER REGISTER	INNER SECONDARY SWIRL	1/BURNER x 4 = 4	OPTIMIZATION IGNITION BURNERS OUT OF SERVICE LOAD CHANGE	ELECTRIC DRIVES COUPLED TO BURNER MANAGEMENT SYSTEM
OUTER REGISTER	OUTER SECONDARY SWIRL	1/BURNER x 4 = 4		
UPPER TERTIARY AIR PORTS	STAGING	9		
LOWER TERTIARY AIR PORTS	STAGING	1		

positions; "burner out of service", light off and normal operations. Limit switches on the tertiary air port drives provided for two positions: "closed and open" (to a fixed setting).

Table 4-2 illustrates the inputs from existing equipment required by the retrofit control system. Numerous interfaces between the existing penumatic controls and electrical circuits and the retrofit system had to be made to provide the necessary control signals. Once completed, the control system was capable of providing fully automatic operation of the burner registers and tertiary port dampers.

The DMB's also incorporated a modern electric/oil ignition system. A Forney Engineering Company High Energy Spark Ignition and oil gun assembly were installed in the center of the core air pipe located in the center of the coal nozzle. An electrical discharge ignites the fuel oil spray that exits from the oil atomizer. The oil flame is used to warm-up the boiler and, subsequently,m iginite the coal. The oil-firing capability (7 million Btu/hr) may also be used to stabilize the coal flame during low load operation or during periods when poor coal quality contributes to burner instability.

As an additional safety feature of the retrofit control system, an improved uninterruptible power supply was installed at the Pearl Station. The system will immediately supply all the power requirements of the burner management system, including all register and tertiary port drives, as well as some station emergency power requirements in the event of a plant power failure. This feature assures that the burner controls will be able to complete a safe shutdown sequence in a low-of-power situation.

4.1.5 Windbox

Extensive redesign of the windbox was required to retrofit the DMB array to the WIPCO boiler. Since the furnace front wall and existing burners were being completely replaced, it was prudent to scrap all but the side walls of the original windbox. A new windbox wall was installed and required

TABLE 4-2. INPUTS REQUIRED FROM EXISTING EQUIPMENT

INPUT	EXAMPLE OF USE
Forced Draft Fan Running	Lightoff
Forced Draft Fan Stopped	MFT (Master Fuel Trip)
High Furnace Pressure	MFT
Air Flow Greater Than Min. (25%)	Purge
Air Heater Running	Lightoff
Air Flow Less Than 25%	MFT
Air Flow Less Than 40%	Permits Lightoff of 1st Ignitor
Turbine Tripped	MFT
Boiler Load Less Than 30%	Pulv. Trip if No Oil and mill Load Less Than 40%
Ignitor Oil Trip Valve Fully Closed	IFT (Ignitor Fuel Trip)
Ignitor Oil Trip Valve Not Fully Closed	Alarm
Ignitor Oil Trip Valve Fully Open	Ignitor Prelight Permissive
Ignitor Oil Trip Valve Not Fully Open	Alarm
Ignitor Oil Header Press. Low	IFT
Ignitor Oil Header Press. High	IFT (Time Delay)
Ignitor Oil/Atom. Air Diff. Low	IFT
Ignitor Oil/Atom. Air Diff. Adequate	Ignitor Prelight Permissive
P.A. Fan Running	Pulv. Start Permissive
P.A. Fan Stopped	Purge Permissive
P.A. Capacity Damper 2 Min.	Mill Start Permissive
Coal Feeder Running	10 Min. to Establish Coal Fire
Coal Feeder Stopped	Closes Burner Shut-Off Valves
Coal Feeder Speed 0 Min.	Feeder Start Permissive
Coal Feeder Speed Less Than 50%	Alarm - Oil Support Req'd.
Pulverizer Running	Indicator Light
Pulverizer Stopped	Indicator Light
Pulverizer Load Less Than 40%	Pulv. Trip Without Oil Support
Burner Shut-Off Damper Open	Pulv. Start Permissive
Burner Shut-Off Damper Closed	Pulv. Trip.

supporting trusses to be located so as not to interfere with burner and tertiary port locations, as well as register drive shafts, instrumentation, etc.

4.1.6 Furnace Wall Structural Considerations

The Pearl Station boiler structure is typical of modern, pulverized coal fired boilers. It is supported from the top, or hung, from large, horizontal steel members which are in turn supported by vertical steel columns. The lower portions of the boiler depend on the furnace wall tubes themselves for support. If a tube is bent, to form an opening in the wall for example, that tube is no longer considered capable of providing lower furnace and ash hopper support.

The retrofit of the DMB burner array, along with the 13 tertiary ports, required the bending of most furnace tubes in the front wall. Foster Wheeler determined that the most cost-effective solution for this problem was to transfer the front wall load to the existing side walls. A single support beam was attached to the hopper slope beneath the front wall and to both side walls. It was necessary to attach the beam to the hopper slope tubes with sliding connections to accommodate thermal expansion. The wall support modification is illustrated in Figures 4-6 and 4-7.

4.2 Foster Wheeler Burner Optimization Program

The original plan was to begin the DMB field evaluation immediately following the equipment installation. However, due to lack of EPA funding, the field evaluation was delayed for 14 months. To ensure that the DMBs could be operating satisfactorily over this period, a series of checkout tests was conducted with the tertiary air ports closed. These tests were conducted by Foster Wheeler using instrumentation and test procedures different from those used in the remainder of the field evaluation. These differences make direct quantitative comparisons tenuous. The primary value of these tests was the definition of operational settings with the tertiary air ports closed.

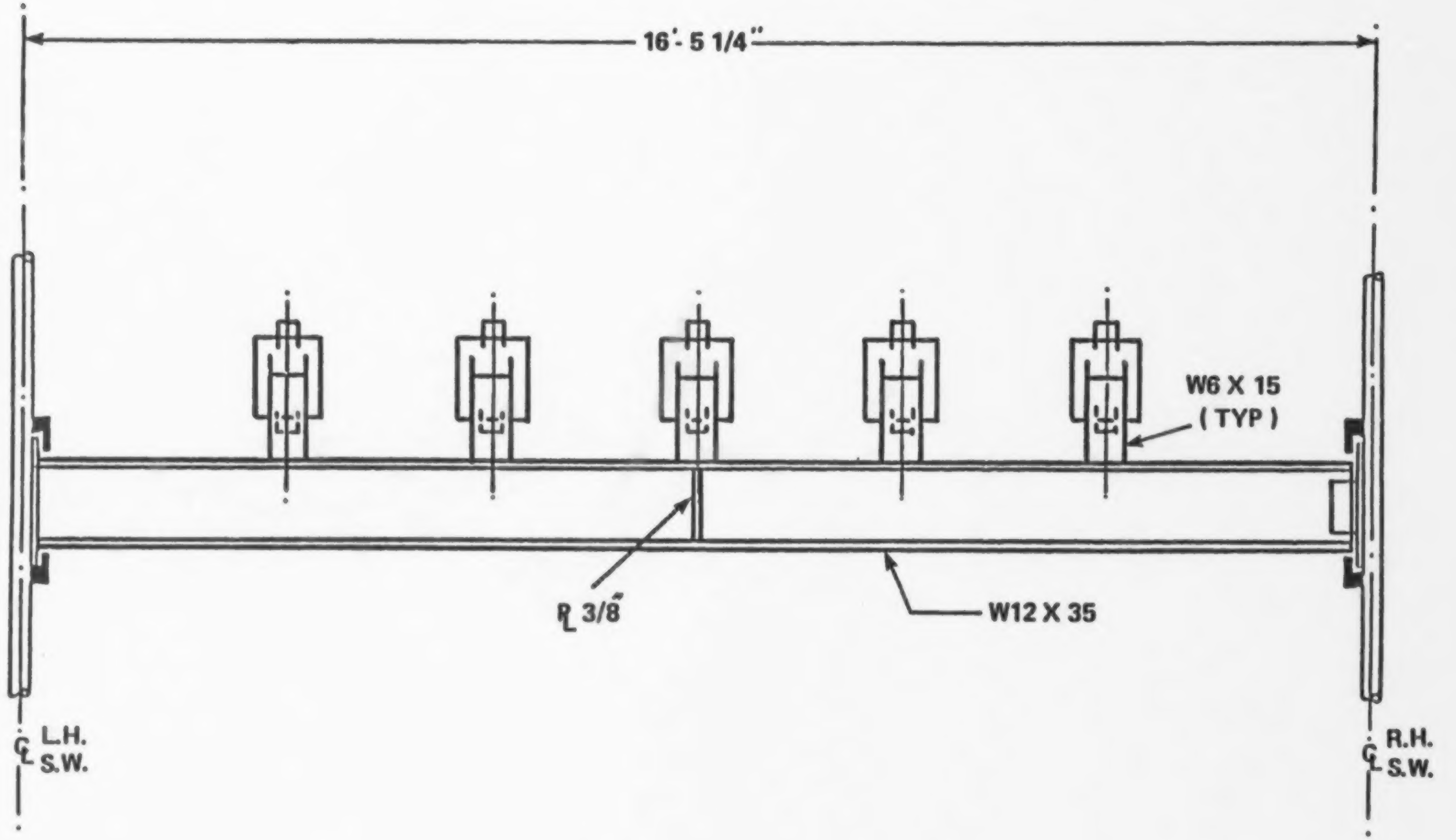

16'-5 1/4"
W6 X 15
(TYP)
W12 X 35
PL 3/8"
℄ L.H. S.W.
℄ R.H. S.W.

Figure 4-6. Front wall support - front view.

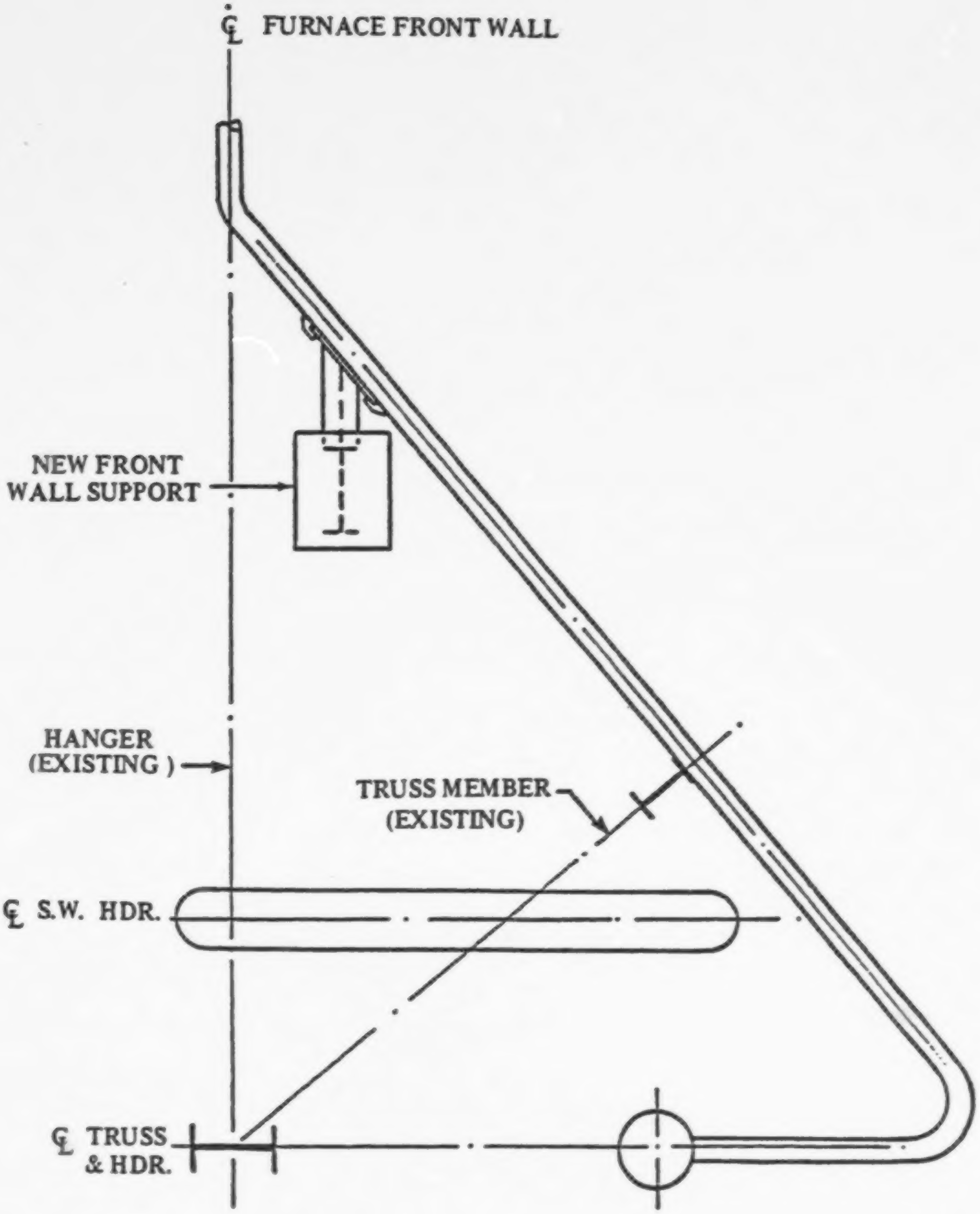

℄ FURNACE FRONT WALL
NEW FRONT WALL SUPPORT
HANGER (EXISTING)
TRUSS MEMBER (EXISTING)
℄ S.W. HDR.
℄ TRUSS & HDR.

Figure 4-7. Front wall support - side view.

4.2.1 Checkout Test Methodology

The burner performance was evaluated over a test matrix of burner settings with the tertiary air ports closed. This included 15 combinations of inner and outer register positions and three nozzle positions. In all cases, the settings on all four burner settings were the same.

Most of the tests were conducted at full boiler load and the design point excess air (approximately 3.3 percent excess O_2). Additional tests were conducted at high excess air and reduced load.

Each test condition was run for a minimum of one hour to ensure that steady operation was achieved before data was collected. During data collection periods, a number of data sets were gathered to statistically minimize the fluctuations that constantly occur during normal boiler operation. Several coal samples were collected during the test program for later analysis.

The following data were collected for each burner test condition:

1. Flue Gas Analysis (NO_x, O_2 and CO).

2. Boiler Steaming Performance (e.g. outlet steam temperature, pressure, and flow rate; feedwater, temperature, pressure, and flow rate).

3. Boiler Air and Fuel Data (air inlet and preheat temperature; fuel flow rate and ultimate analysis; flue gas temperature across airheater).

4. Coal and flyash samples on a daily basis.

4.2.2 Checkout Test Results

A summary of the test data is shown in Table 4-3. The table is divided into three parts. The first part includes data collected at full load and design excess air levels. The second included data collected at full load but at higher than design excess air levels. The final section summarizes lower load test conditions. The data compiled for each test are flue gas concentrations (NO_x, CO, and O_2); boiler load, expressed as MW_e generation; inner and outer register position measured in degrees open; nozzle position expressed as inches from nominal design position; steam temperature in ^oF; efficiency loss due to unburned carbon in the ash in percent; and calculated boiler efficiency in percent.

Figures 4-8 through 4-14 were generated from the data collected to assist in determining the optimum DMB register and nozzle positions. Figures 4-8 through 4-13 illustrate the effect of register position on NO_x emissions for constant excess air and nozzle position. Figure 4-14 illustrates the effect on NO_x emissions of varying nozzle position for various register positions and excess air levels.

4.2.3 Optimum Burner Configuration

A review of Figures 4-8 through 4-14 forms the basis for the final recommended burner configuration by Foster Wheeler as the "optimum" from which to begin the staged combustion tests to be performed by EER. Several important points should be noted:

- NO_x emission levels are lower for virtually all burner configurations at lower excess air conditions. Therefore, the DMB system should be operated as close as possible to the boiler design excess air levels.

- In general, NO_x emissions were lower as both inner and outer air registers were in more closed positions (<30^o open). By nature of the manner in which the register controls air flow, these positions

TABLE 4-3. DATA SUMMARY

Part 1 Full Load, Design Excess Air

TEST No.	NOx 1.b/E6B	CO* ppm	O2 %	LOAD MWG	Ri des	Ro open	S/N in.	FST F	Luc %	EFFICIENCY %
1.10	0.603	79	3.18	20	15	30	0	875	0.75	85.257
1.20	0.700	112	3.41	20	15	45	0	860	0.84	85.379
1.30	0.750	84	3.38	20	15	60	0	860	0.84	85.389
2.10	0.602	63	3.23	20	30	30	0	882.5	0.52	85.633
2.20	0.696	95	3.33	20	30	45	0	842	0.84	85.675
2.30	0.770	71	3.30	20	30	60	0	870	0.52	85.660
3.10	0.629	94	3.30	20	45	30	0	892.5	0.29	85.542
3.20	0.668	93	3.33	20	45	45	0	860	0.20	85.937
3.30	0.740	72	3.39	20	45	60	0	862.5	0.29	85.507
4.10	0.625	85	3.13	20	60	30	0	875	0.14	85.578
4.20	0.673	61	3.40	20	60	45	0	845	0.14	85.485
4.30	0.653	57	3.28	20	60	60	0	895	0.52	85.686
5.10	0.668	80	3.37	20.5	75	30	0	890	0.14	85.522
5.20	0.641	59	3.27	20.5	75	45	0	860	0.14	85.546
5.30	0.655	74	3.45	20	75	60	0	850	0.14	85.469
1.40	0.552	222	3.33	20	15	30	+4	887.5	0.75	85.455
1.41	0.534	62	3.20	20	15	30	+4	880	0.32	86.232
1.42	0.574	138	3.28	20	15	30	+4	865	0.66	86.141
1.50	0.625	99	3.25	20	15	45	+4	885	0.75	85.449
1.60	0.741	70	3.26	20	15	60	+4	875	1.38	85.097
2.40	0.615	78	3.39	20	30	30	+4	877.5	1.38	85.132
2.50	0.701	86	3.13	21	30	45	+4	877.5	0.57	86.100
2.60	0.701	49	3.02	20	30	60	+4	855	1.38	84.985
3.40	0.659	62	3.40	20	45	30	+4	890	1.38	85.066
3.50	0.703	71	3.25	20.5	45	45	+4	877.5	0.57	86.061
3.60	0.738	61	3.18	20	45	60	+4	870	1.09	84.985
4.40	0.656	97	3.18	20	60	30	+4	897.5	1.09	84.975
4.50	0.652	76	3.30	20	60	45	+4	890	1.09	85.085
4.60	0.656	70	3.18	20	60	60	+4	870	1.09	85.110
5.40	0.683	83	3.16	19.5	75	30	+4	855	0.56	84.563
5.50	0.642	73	3.10	20	75	45	+4	837.5	1.22	84.841
5.60	0.649	65	3.29	20	75	60	+4	837.5	1.22	84.428
1.70	0.691	59	3.20	21	15	30	-3	887.5	0.39	85.272
1.80	0.696	49	3.39	20.5	15	45	-3	860	0.26	85.424
1.90	0.805	59	3.60	20.5	15	60	-3	865	0.26	85.346
2.70	0.695	64	3.33	21	30	30	-3	890	0.39	85.229
2.80	0.695	49	3.39	20	30	45	-3	860	0.26	85.411
2.90	0.761	56	3.36	20.5	30	60	-3	890	0.39	85.400
3.70	0.664	54	3.39	20	45	30	-3	870	0.45	85.405
3.80	0.646	57	3.33	20.5	45	45	-3	880	0.39	85.404
3.90	0.728	49	3.35	20.5	45	60	-3	880	0.39	85.401
4.70	0.661	40	3.35	20	60	30	-3	880	0.45	85.419
4.80	0.707	43	3.40	20	60	45	-3	855	0.45	85.403
4.90	0.748	45	3.36	20	60	60	-3	860	0.45	85.419
5.70	0.651	46	3.26	20	75	30	-3	882.5	0.45	85.633
5.80	0.710	66	3.40	20	75	45	-3	865	0.45	85.576
5.90	0.742	49	3.42	20	75	60	-3	865	0.45	85.394

TABLE 4-3. DATA SUMMARY (Continued)

Part 2 Full Load, High Excess Air

TEST No.	NOx lb/E6B	CO* ppm	O2 %	LOAD MWG	Ri deg	Ro open	S/N in.	FST F	Luc %	EFFICIENCY %
1.11	0.853	73	5.36	20	15	30	0	917.5	0.14	84.468
1.21	0.767	69	5.18	20.5	15	45	0	867.5	0.20	84.821
1.31	0.933	50	5.28	20.75	15	60	0	887.5	0.20	84.781
2.11	0.857	58	5.52	21	30	30	0	895	0.20	84.536
2.21	0.781	63	5.41	21	30	45	0	870	0.20	84.722
2.31	0.935	55	5.31	21	30	60	0	880	0.20	84.768
3.11	0.840	59	5.56	21	45	30	0	912.5	0.20	84.684
3.21	0.921	70	5.65	21	45	45	0	900	0.20	84.513
3.31	0.901	47	5.34	20.5	45	60	0	870	0.18	85.074
4.11	0.852	55	5.70	21	60	30	0	915	0.18	85.924
4.21	0.835	48	5.20	21	60	45	0	880	0.18	85.265
4.31	0.857	46	5.40	21	60	60	0	870	0.18	85.178
5.11	0.834	62	5.64	21	75	30	0	920	0.18	85.952
5.21	0.810	65	5.09	20.5	75	45	0	875	0.26	84.800
5.31	0.837	40	5.30	20.5	75	60	0	875	0.26	84.718
1.43	0.742	68	5.50	20	15	30	+4	927.5	0.32	84.811
1.51	0.786	38	5.30	20.5	15	45	+4	932.5	0.12	85.567
1.61	0.869	46	5.45	20	15	60	+4	915	0.12	85.602
2.41	0.670	59	5.58	20	30	30	+4	945	0.12	85.562
2.51	0.841	47	5.25	20.5	30	45	+4	940	0.12	85.539
2.61	0.834	63	5.38	20	30	60	+4	900	0.12	85.777
3.41	0.741	43	5.44	20	45	30	+4	907.5	0.34	85.018
3.51	0.866	56	5.60	20	45	45	+4	880	0.34	85.942
3.61	0.851	64	5.60	20	45	60	+4	870	0.34	85.961
4.41	0.884	56	5.50	20	60	30	+4	942.5	0.41	84.100
4.51	0.820	53	5.38	20	60	45	+4	915	0.41	84.140
4.61	0.851	78	5.43	20	60	60	+4	870	0.34	85.038
5.41	0.949	66	5.50	20	75	30	+4	935	0.41	83.924
5.51	0.855	56	5.35	20	75	45	+4	915	0.41	83.990
5.61	0.845	41	5.26	20	75	60	+4	895	0.41	84.343
1.71	0.814	49	5.46	20.5	15	30	-3	870	999	999
1.81	0.806	39	5.41	20	15	45	-3	900	0.24	85.258
1.91	0.912	35	5.48	20	15	60	-3	900	0.24	85.223
2.71	0.789	31	5.50	20.5	30	30	-3	872.5	999	999
2.81	0.765	49	5.61	20	30	45	-3	880	999	999
2.91	0.908	49	5.50	20	30	60	-3	895	0.24	85.209
3.71	0.824	52	5.25	20	45	30	-3	900	0.24	85.324
3.81	0.818	54	5.41	20	45	45	-3	880	0.24	85.251
3.91	0.904	47	5.43	20.5	45	60	-3	887.5	0.24	85.244
4.71	0.832	39	5.28	20	60	30	-3	907.5	0.24	85.310
4.81	0.845	38	5.50	20	60	45	-3	885	0.24	85.210
5.71	0.778	27	5.20	20	75	30	-3	895	999	999

TABLE 4-3. DATA SUMMARY (Continued)

Part 3 Reduced Load

TEST No.	NOx 1b/E6B	CO* ppm	O2 %	LOAD MWG	Ri deg	Ro open	S/N in.	FST F	Luc %	EFFICIENCY %
1.46	0.717	50	3.28	15.0	15	30	+4	804	0.60	86.001
1.47	0.806	63	5.55	15.2	15	30	+4	845	0.43	86.155
1.48	0.788	36	3.35	12.5	15	30	+4	801	0.47	86.033
1.49	0.934	66	5.41	13.0	15	30	+4	843	0.39	84.984
15.4	0.604	72	3.40	19.5	15	15	+4	867.5	0.56	84.540
15.5	0.764	55	5.38	19.5	15	15	+4	900	0.56	84.108

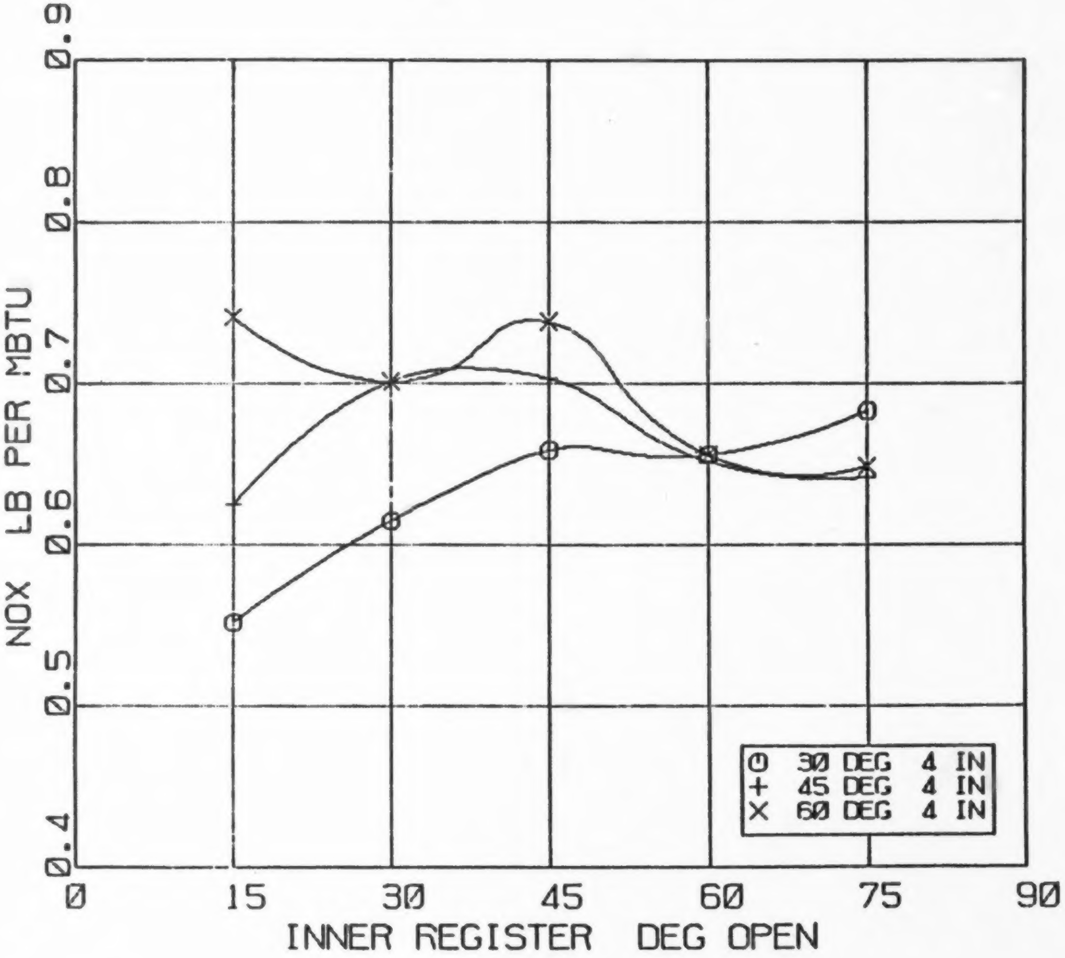


Figure 4-8. Influence of inner register position on NO_x emissions for various outer register positions at 3.3% O_2 for a nozzle setting of 4 inches.

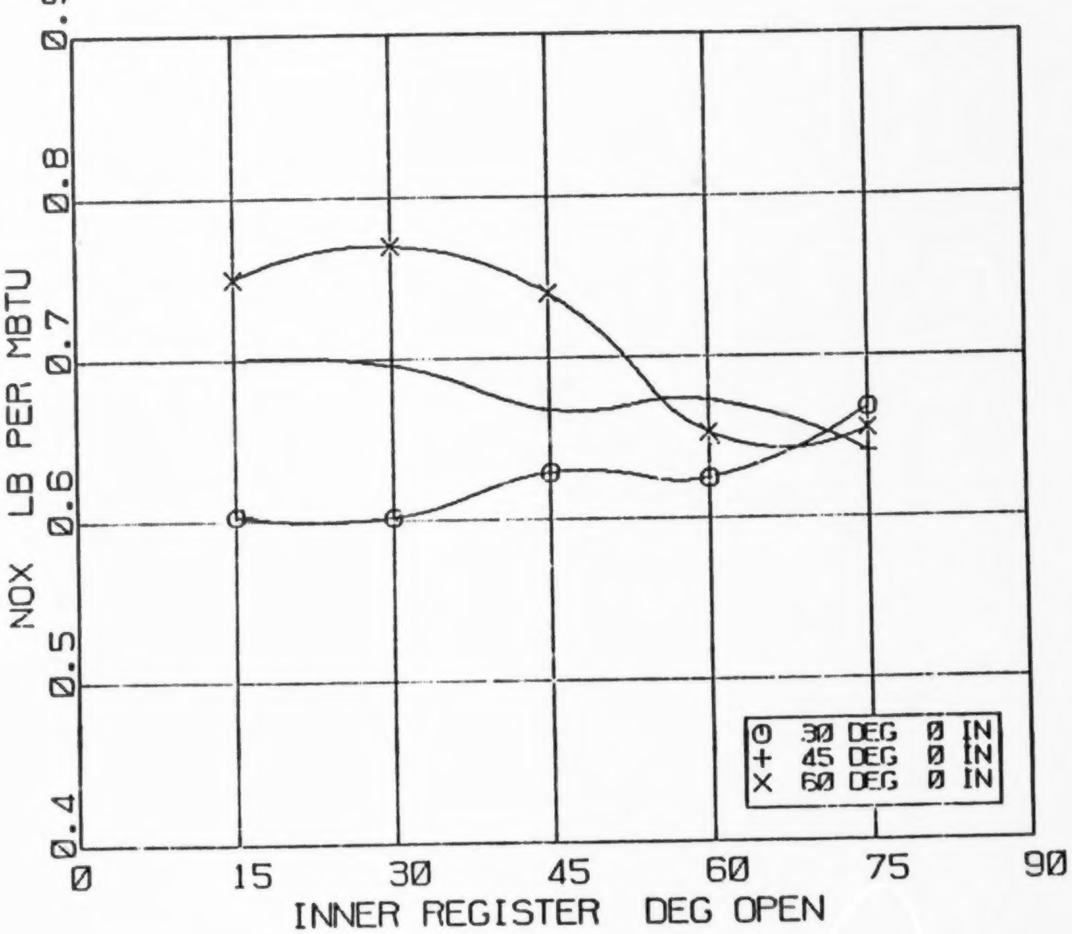


Figure 4-9. Influence of inner register position on NO_x emissions for various outer register positions at 3.3% O_2 for a nozzle setting of 0 inches.

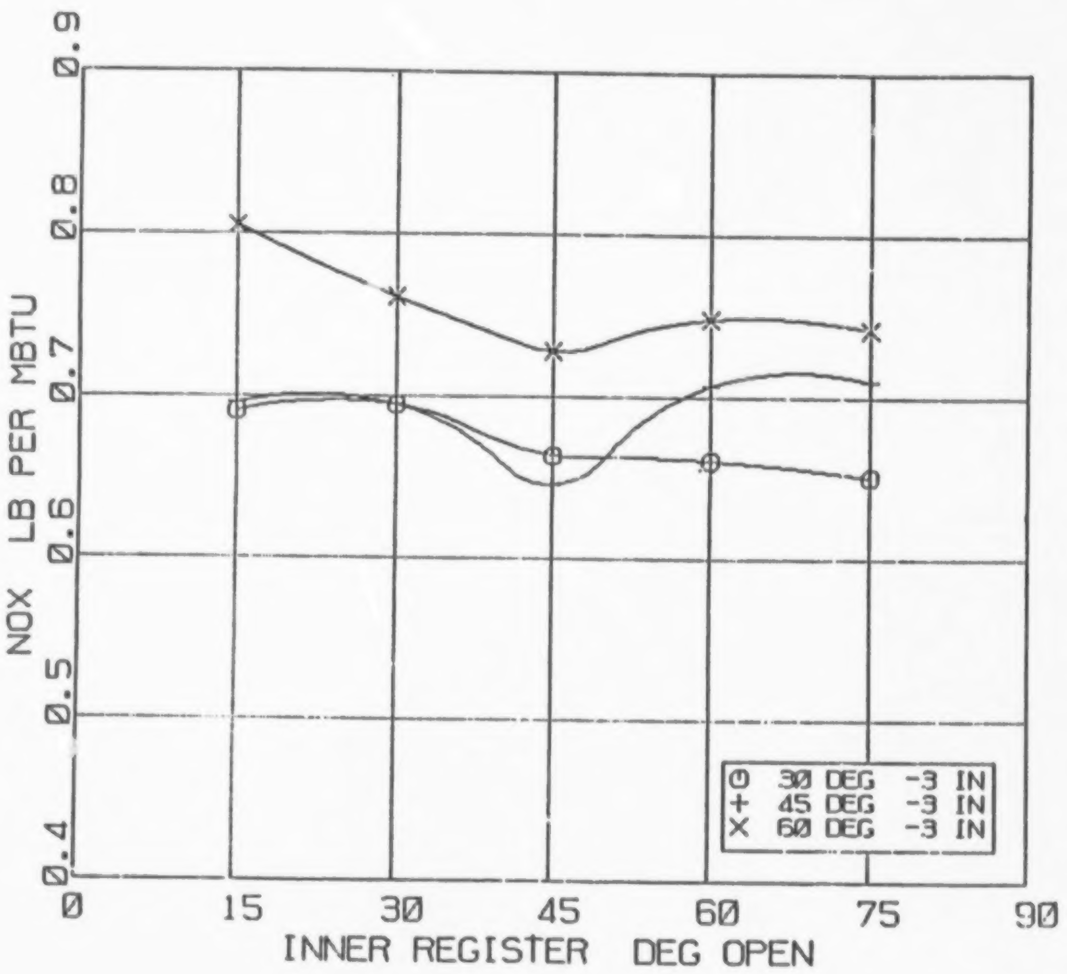


Figure 4-10. Influence of inner register position on NO_x emissions for various outer register positions at 3.3% O_2 for a nozzle setting of -3 inches.

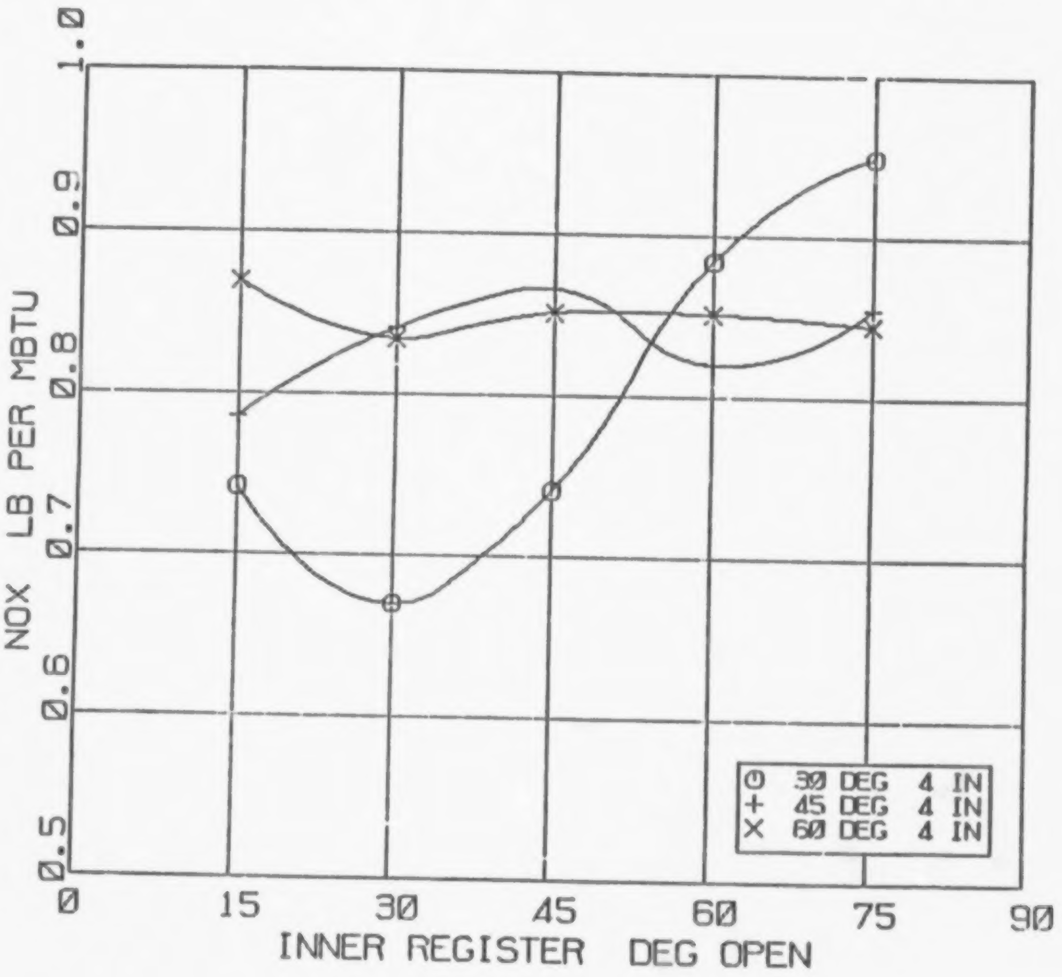


Figure 4-11. Influence of inner register position on NO_x emissions for various outer register positions at 5.5% O2 for a nozzle setting of 4 inches.

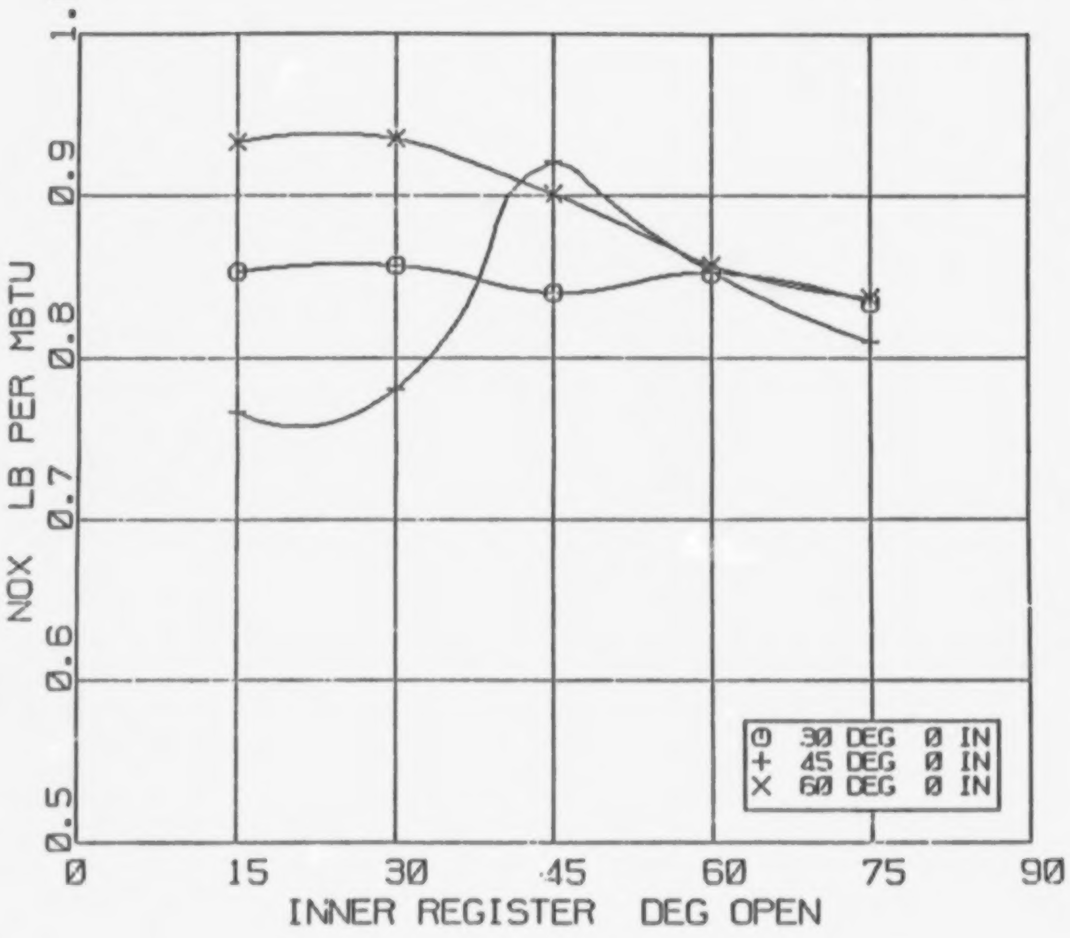


Figure 4-12. Influence of inner register position on NO_x emissions for various outer register positions at 5.5% O_2 for a nozzle setting of 0 inches.

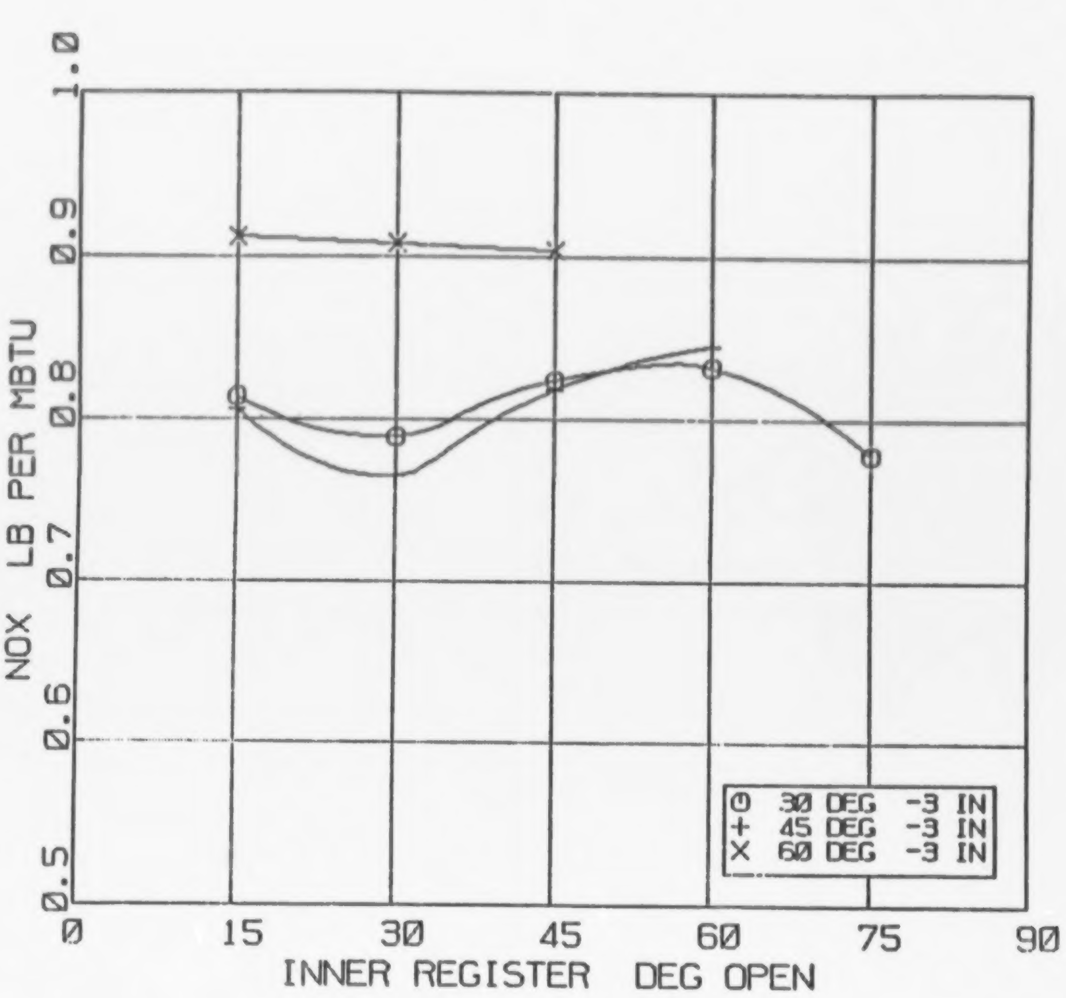


Figure 4-13. Influence of inner register position on NO_x emissions for various outer register positions at 5.5% O_2 for a nozzle setting of -3 inches.

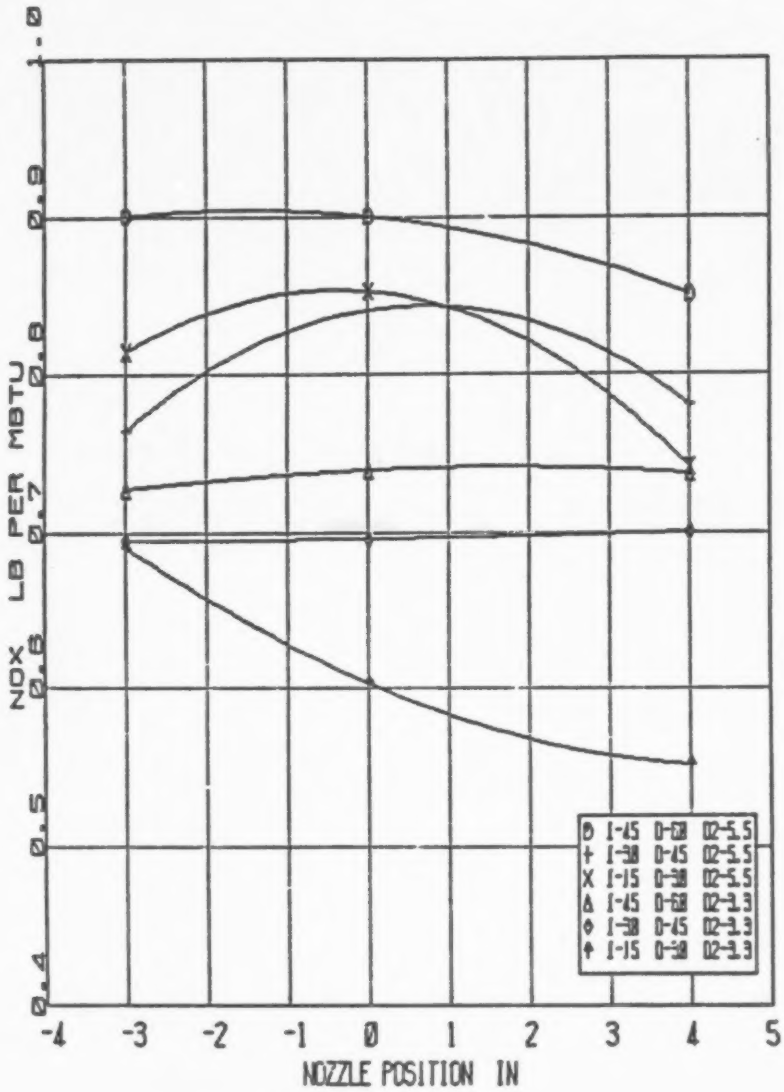


Figure 4-14. NO_x emissions as a function of nozzle position, register position, and excess air.

impart a greater amount of swirl to the secondary air. However, simultaneously, the more closed register positions increase the windbox static pressure and consequently force additional combustion air through the tertiary air ports thereby lowering the primary burner zone stoichiometry. These effects can not be separately based on the checkout test data.

- NO_x emissions were lowest with the coal nozzle in the position closest the furnace (approximately 4" in front of the nominal design position). This configuration provides the smallest coal/primary air flow annulus and therefore the highest velocity.

Based on the above conclusions, Foster Wheeler recommended proceeding with the staged combustion performance evaluation of the DMB with the following burner settings:

Inner Register Position = 15° Open
Outer Register Position = 30° Open
Nozzle Position = +4 inches
Register Sleeves = 100 percent Open

As a final demonstration of acceptable boiler operation at these recommended optimum burner settings, Foster Wheeler collected data on several additional days as the DMB was being operated by the WIPCO operations staff. NO_x emissions were consistantly below 0.6 lb/10^6 Btu, CO emissions were always less than 200ppm, and boiler performance was judged completely acceptable by the WIPCO management. In addition, to verify that the burner would continue performing properly during the staged combustion optimization tests a final brief (1 hr) test condition was investigated. The uppermost elevation of tertiary ports were opened to reduce the primary burner zone stoichiometry to approximately 92 percent. The NO_x emissions during this test dropped to almost 0.4 lb/MMB while boiler performance appeared unchanged.

These initial optimization tests were successful in identifying burner settings which enabled WIPCO to operate the Pearl Station in a satisfactory manner while achieving NO_x emission reductions of approximately 50 percent from the uncontrolled levels of the original Intervane Burners.

4.3 DMB Optimization: Approach and Procedures

4.3.1 DMB Field Evaluation Chronology

The optimization tests began in November, 1982. Little progress was made during November and December, 1982 due to the need to bring the measurement system on line after the long dormant period and inclement weather including flooding of the Illinois River which forced the plant to shutdown in December.

The initial testing strategy was to leave the burner settings at those normally used by the operators for unstaged operations (tertiary ports closed) and then to begin opening the tertiary ports. This reduced the burner zone stoichiometry to about 85 percent theoretical air and reduced NO_x emissions to less than 0.7 lb/MMB.

To reduce the burner zone stoichiometry further it was necessary to divert additional air from the burner throats to the tertiary ports. This was accomplished by almost fully closing the register sleeves. At that sleeve position, burner zone stoichiometry near the design point, 70 percent theoretical air, could be achieved. However, flame shape adjustment became impossible because each of the available controls was being fully utilized to achieve the desired air flow split between the burner throat and tertiary ports. It should be noted that this is a consequence of the design of the Pearl Station DMBs to enable their operation under both staged and unstaged conditions. NO_x emissions of 0.3 lb/10^6 Btu were achieved under these conditions in March, 1983.

A tube leak unrelated to the DMB operation occurred in late March and the scheduled spring outage was begun early. During this outage the burner components were inspected and found to be in good condition. However, several of the adjustable sleeves were found to be misaligned. These were straightened prior to resuming testing in April.

Since low NO_x emissions (0.3 $lb/10^6$ Btu) had been achieved, the subsequent testing focus on identifying burner settings suitable for long term operation. It was found that low NO_x emissions, adequate flame stability and low carbon loss required careful adjustments to balance the four burners. This was extremely difficult since any changes in burner settings generally increased the burner zone stoichiometry increasing NO_x emissions. Also, low NO_x emissions required that the flames be adjusted to minimize pre-mixing of the coal with the secondary air streams. This involved adjusting the burner controls so that the base of the flame was within the burner exit or adjacent to the firing face. The operators were reticent to operate at these conditions due to concerns over possible coal nozzle over heating and eyebrow formation. The coal nozzles were equipped with thermocouples to monitor metal temperatures at the nozzles tips. Throughout the testing, these thermocouples indicated approximately windbox temperature. The operators concerns were related to previous experiences involving nozzle failure. Eyebrow formation was a persistent problem with the original equipment Intervane burners as well as the retrofit DMBs. Normally the operators poked the eyebrows through the inspection ports once per shift. For these reasons it was decided to select a more conservative operating conditions for long term operation at the expense of higher NO_x emissions.

The burners were adjusted to produce uniform excess O_2 and CO distributions in the exhaust duct upstream of the air heater indicating balanced burners. NO_x emissions were in the range of 0.4 $lb/10^6$ Btu. With these settings, a 30-day test was begun in May, 1983. This involved operation of the unit under the control of the WIPCO operators over the normal duty cycle maintaining the settings specified by EER. Measurements included continuous emissions monitoring and manual measurements of emissions and performance parameters. During the test, the pulverized coal fineness degraded and burner imbalance developed resulting in high carbon loss at the nominal operating excess O_2. The pulverizers were adjusted to improve fineness and the excess O_2 was increased to reduce carbon loss. This increased NO_x emissions.

Since the settings selected for the first 30-day test were clearly not acceptable for long term operation, additional optimization tests were conducted during the summer of 1983. A second 30-day test was initiated in August, 1983 using alternate burner settings selected to avoid burner imbalance. After about 2 weeks of operation, excessive slagging was observed. The burner settings were altered and the excess air was increased to permit continued operation until the fall outage. Again, this increased NO_x emissions.

The furnace was cleaned during the scheduled fall outage in October and the burners were inspected and found to be in good condition. However, some of the sleeves were found to be misaglined once again. Following the outage additional optimization tests were conducted with the clean furnace and another set of operating conditions was selected for continuous monitoring in December, 1983. During this period the operators were requested to use the specified settings as a guide and to make adjustments as required to achieve normal burner/boiler performance.

The objective for the remainder of the testing period was to obtain continuous emissions data for the longest possible time period with the minimum NO_x emissions compatible with acceptable burner/boiler performance. Continuous monitoring resumed in mid-January, 1984. However, slagging occurred and an outage to clean the furnace was required in February, 1984. Following the outage, a flame scanning system problem prevented opening the tertiary air ports until late March when a few additional days of continuous monitoring data were obtained.

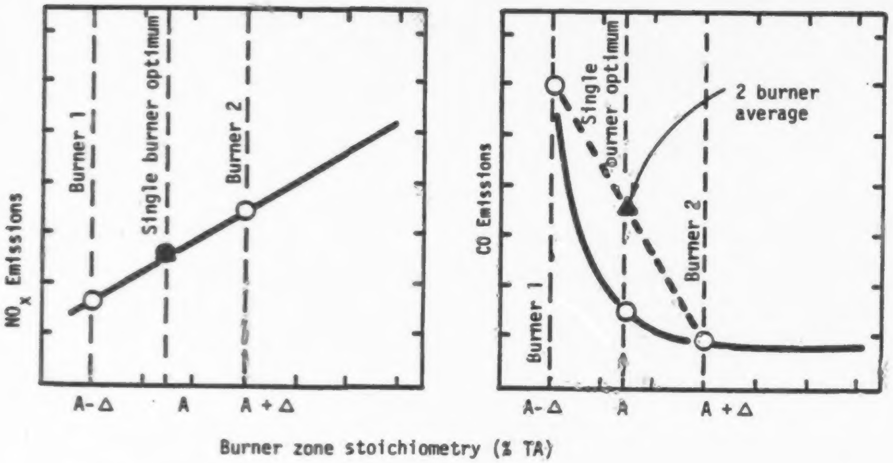
Restoration commenced in April, 1984. The restoration was limited to removal of the corrosion panels, some final adjustments to the burner management system and other components, and tack welding of the register sleeves in the fully open position. The tertiary air ports were left in a fully operational condition. Because WIPCO presently has no NO_x emission limits, subsequent operation has been mainly with the tertiary air ports closed.

4.3.2 Multi-Burner DMB Control

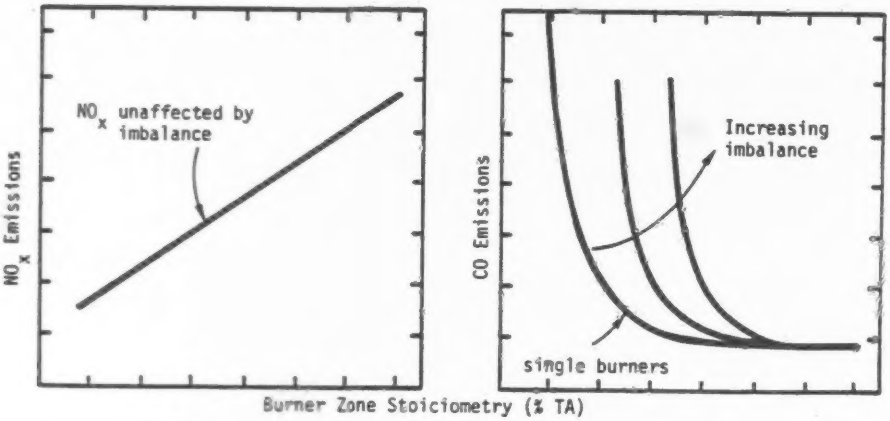
The prototype DMB tests in the new LWS demonstrated that burner performance was influenced strongly by burner settings. During the tests of the final prototype burner, the effects of primary velocity, register settings and core air valve settings were evaluated for fixed burner zone stoichiometry and excess air. While acceptable flame stability was maintained over fairly wide ranges, the specific settings influenced flame stand off distance, width and length as well as NO_x and CO emissions. This suggests that optimum performance at WIPCO requires optimization of these variables.

The prototype burner tests also demonstrated that the burner zone stoichiometry was a key operating variable. Generally, NO_x decreased approximately linearly as burner zone stoichiometry was decreased. CO emissions were low (and combustion efficiency was high) for high burner zone stoichiometry and remained low as burner zone stoichiometry was reduced to a critical value where CO emissions increased sharply (combustion efficiency decreased sharply). Thus, the optimum operating condition was burner zone stoichiometry slightly above the knee of the CO curve. In a multi-burner array with all of the burners operating at the same burner zone stoichiometry and similar register settings etc, the overall performance of the array is the same as that of the individual burners. However, if the burners are imbalanced, i.e. the burners do not all operate at the same conditions, the overall performance of the multi-burner array in terms of CO and NO_x emissions will be an average of the performance of the individual burners.

The effect of imbalance on a two-burner array is illustrated in Figure 4-15A. Typical NO_x and CO versus burner zone stoichiometry curves are shown. The optimum performance for a single burner occurs at burner zone stoichiometry A. If two burners are operated at the same average



A. Two burners with moderate imbalance.



B. Effects of increasing imbalance (2 or more burners)

Figure 4-15. Impacts of imbalance in a multi-burner array.

stoichiometry, A, but are imbalanced by an amount, there is no impact on NO_x emissions since the NO_x versus burner zone stoichiometry curve is approximately linear over this range. However, the average CO emissions are increased sharply since one burner is operating beneath the knee of the CO curve. Since the optimum operating point for the single burner was established based on CO emissions and the CO emissions for the two unbalanced burners are higher, this operating condition is unacceptable for the two burner array. To reduce CO emissions, the average burner zone stoichiometry must be increased so that both burners operate above the knee of the CO curve. This increases NO_x emissions.

The overall effects of imbalance on an array of two or more burners are illustrated in Figure 4-15B. As the degree of imbalance increases, the knee of the CO curve moves to higher burner zone stoichiometries. The NO_x versus burner zone stoichiometry curve remains unchanged as the imbalance increases. However, to maintain a fixed level of CO emissions, the burner zone stoichiometry but be increased as the degree of imbalance increases. This results in an NO_x emissions increase.

4.3.3 DMB Control at WIPCO

At WIPCO, the adjustment of the individual burners, burner balancing and adjustment of burner zone stoichiometry were complicated due to two factors: the common windbox and the requirement for operation of the burners under both staged and unstaged conditions. In the WIPCO boiler, all combustion air except tempering air to the pulverizers is supplied to the top of the windbox. Hot air is directed to the pulverizers from two ducts at the bottom corners of the windbox. The total air flow rates to each pulverizer are metered by venturi flow meters. The balance between hot air from the windbox and cold tempering air is controlled to achieve the desired pulverizer exhaust temperature. The remainder of the air entering the windbox exits to the furnace through various burner passages (three per burner or twelve total) and the tertiary air ports (a total of thirteen ports). The air flow distribution among these 25 passages is controlled by the relative restriction in each passage. This provides for very complicated adjustment since changing the restriction in any one passage impacts the flow rates in all passages. This is illustrated in Table 4-4 which shows how the 36 separate adjustable controls affect individual burner performance, burner balancing and burner zone stoichiometry. These controls can be divided into three major groups based on their effects on unit operation. The first group includes the coal nozzles only. They affect burner performance as was demonstrated by the prototype burner tests. However, in the WIPCO installation, the coal nozzles affect burner balance also. Each pulverizer supplies two burners and the coal/primary air flow rate distribution between burners is determined by the relative restriction in the two streams from the "T" at the pulverizer exit through the coal nozzles. Thus, varying the position of one coal nozzle causes a change in the restriction in the primary coal/air path and this alters the flow rate distribution between the two burners supplied by the same pulverizer.

The second group of controls includes the burner sleeves, registers and core air valves which 24 separate adjustments. These variables affect burner performance as was discussed during the prototype burner test. Also they impact burner balance and burner zone stoichiometry by varying the restriction in the air flow paths supplying the burner throats. The third group of controls includes the tertiary air ports only. They impact burner zone stoichiometry only.

Since this was the first installation of DMBs on a field operating boiler in the United States, the burners were designed to operate unstaged as well as staged. This complicated the design and operation of the system since the flow rate through the secondary air passages under staged conditions (120 percent TA) was twice as great as under staged conditions (70 percent TA) assuming a constant primary stoichiometry of 20 percent TA. For fixed burner settings the windbox to furnace pressure differential is approximately proportional to the square of the flow rate. Thus, if the burner settings remained fixed, the windbox to furnace pressure differential would be four times as high under unstaged conditions as under staged conditions. The design point windbox to furnace pressure differential for the Intervane burners was 3.5 in. H_2O. If the DMBs were designed to operate

TABLE 4-4. IMPACTS OF CONTROL CHANGES

CONTROL	TOTAL NUMBER OF CONTROLS	IMPACTS OF CHANGING CONTROL		
		BURNER PERFORMANCE	BURNER BALANCING	BURNER ZONE STOICHIOMETRY
COAL NOZZLE	4	X	X	
INNER SLEEVES	4	X	X	X
OUTER SLEEVES	4	X	X	X
CORE VALVES	4	X	X	X
INNER REGISTERS	4	X	X	X
OUTER REGISTERS	4	X	X	X
TERTIARY AIR PORTS	10			X

staged at this differential pressure, the same burner settings would require 14.0 in. H_2O differential pressure under unstaged conditions. This far exceeds the capabilities of the existing fan system. Alternately if the DMBs were designed to achieve 3.5 in. H_2O differential pressure under unstaged conditions, the pressure drop under staged conditions would be only 0.88 in. H_2O. This low differential pressure makes flow control difficult since pressure drops within the windbox impacted by the flow to the pulverizer ducts which could result in pressure gradiants within the windbox. The normal velocity head for flow through the secondary air passages is 0.40 in. H_2O leaving only a 0.44 in. H_2O differential for controlling the flow.

The solution was to design the burners to produce acceptable pressure drop under unstaged conditions and to increase the restrictions on the burner passages supplying the throat under staged conditions. This required partially closing the registers, sleeves and core air valves.

Of course, to make a transition from unstaged to staged conditions, the flow of air through the tertiary air ports must be increased from zero to an amount approximately equal to that passing through the burner throats. Actually, zero flow through the tertiary air ports would not be acceptable under unstaged conditions since slag could build up in the ports interfering with normal operation. Thus, the tertiary air ports were designed to operate with some leakage air. Because of this it was not possible to operate the burners totally unstaged.

The adjustment of burner zone stoichiometry is summarized in Figure 4-16 for conditions with primary and overall stoichiometries of 20 and 120 percent TA respectively. The data bands show the pressure drops across the aggregates of the tertiary air ports and burner throats as the burner controls are adjusted. Since the pressure drops across the burner throats and tertiary air ports must be equal, the cross hatched area in Figure 4-16 indicates the range of possible burner operating conditions. The highest burner zone stoichiometry is achieved with the tertiary air ports closed and the registers and sleeves adjusted for minimal restriction through the burner throats. This is about 100 percent TA (Point A). Opening the tertiary air

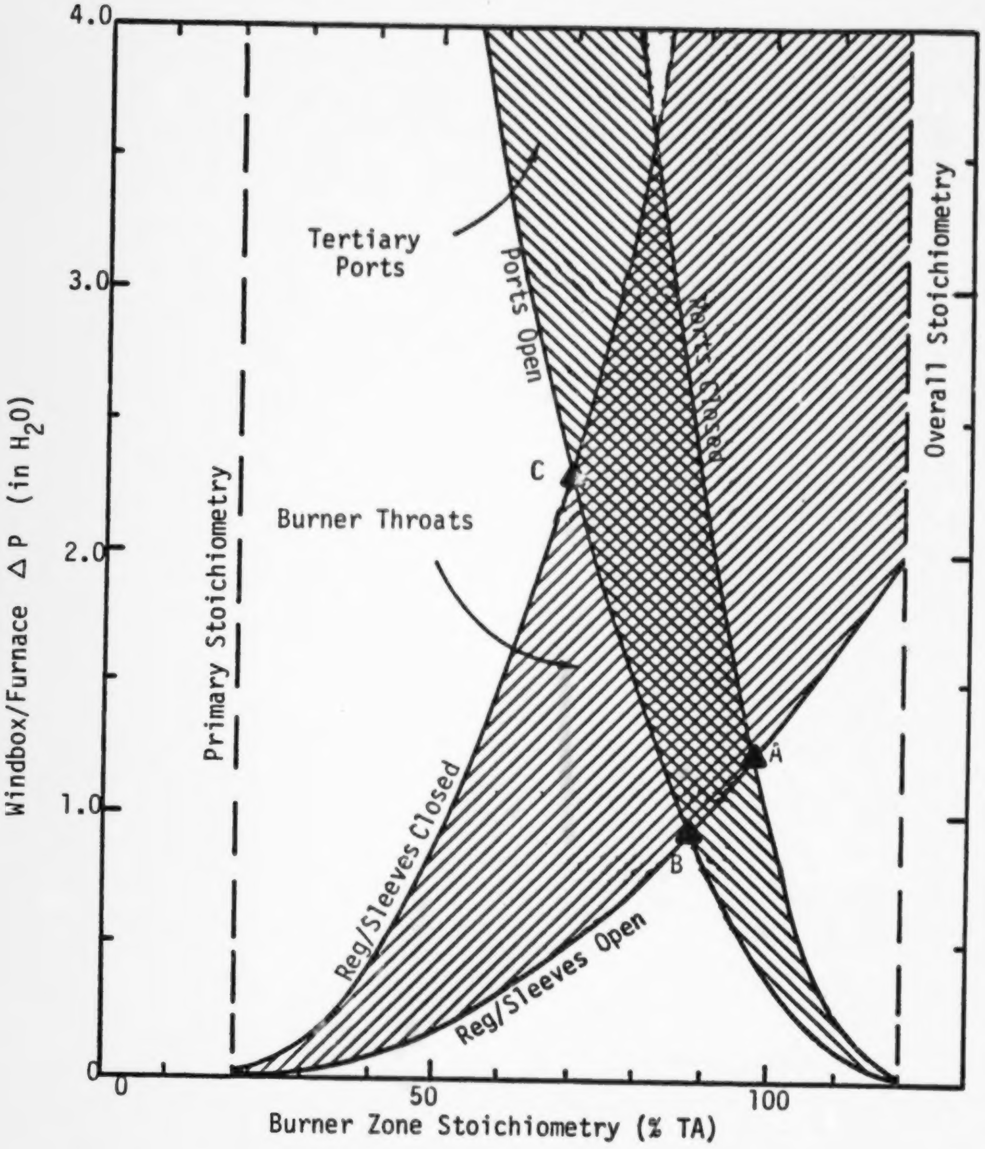


Figure 4-16. WIPCO DMB operating range.

ports fully reduces the burner zone stoichiometry slightly to about 90 percent TA (Point B). To achieve burner zone stoichiometries in the DMB range it is necessary to direct more air from the burner throats to the tertiary air ports. Since the tertiary air ports are already fully open (at Point B), the registers and sleeves must be closed. This increases the windbox to furnace pressure differential and reduces the burner zone stoichiometry to about 70 percent TA (Point C).

Thus, to achieve burner zone stoichiometries close to the DMB design point, it is necessary to operate with the tertiary air ports fully opened and the controls on the burner throats nearly fully closed. The difficulty with this configuration is that there is little leeway for using these controls to optimize burner flame pattern or other performance aspects and burner balancing. Generally, to optimize flame shape and balance the burners it was necessary to increase the burner zone stoichiometry which increased NO_x emissions.

The arrangement of the tertiary air ports affected burner operation also. Based on the tests of the four burner array of development DMBs in the old LWS, the DMB performance degraded when the tertiary air was not distributed symmetrically around each burner. Although the tertiary air port array installed at WIPCO is symmetric horizontally, it is not symmetric vertically or horizontally with respect to each burner. This is illustrated in Figure 4-17 which shows the relative air flows achieved for constant velocities through each port. It should be noted that the ideal tertiary air port array illustrated in Figure 4-1 would produce a uniform distribution: i.e. all numbers would be 100 percent. The right side of Figure 4-17 shows that the tertiary air flow is heavily biased towards the upper burners. The left side of the figure shows that the distribution around each burner is not symmetric. The lower burners have much more tertiary air supplied to the lower outside corners. The upper burners have much more air supplied above the burners. Close examination of Figure 4-17 reveals that one major reason for the vertical imbalance of tertiary air flow rate is the large size (and hence flow rate) of the upper tertiary air ports. Partially closing these ports would help to balance the tertiary air flow rates but this increases

Values are percent of ideal flow rate for uniform distribution

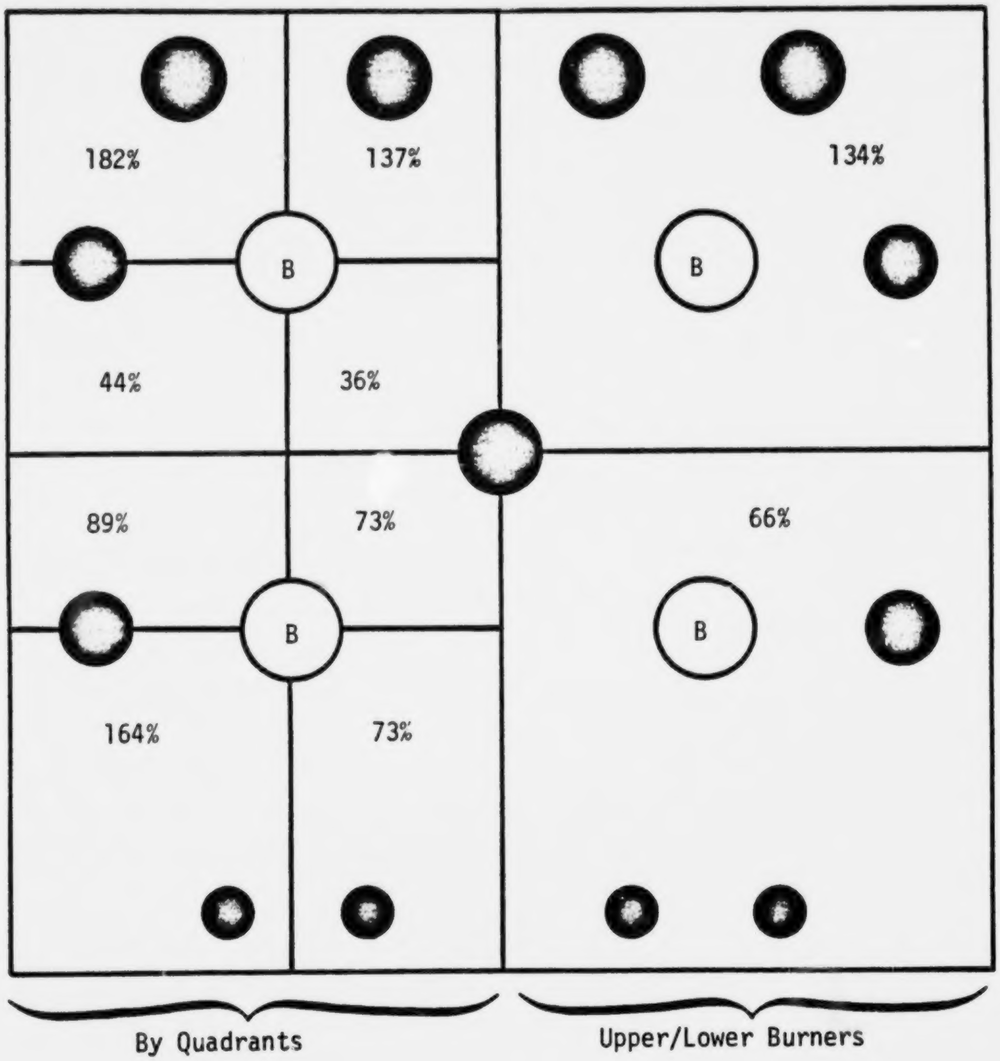

182%
137%
134%
B
B
44%
36%
89%
73%
66%
B
B
164%
73%
By Quadrants
Upper/Lower Burners

Figure 4-17. Tertiary air flowrate distribution (at constant velocity).

burner zone stoichiometries. Due to the effect, minimum NO_x emissions during the WIPCO optimization tests were always obtained with all tertiary air ports opened fully.

4.3.4 DMB Testing at WIPCO

The burner zone stoichiometry and burner balance are key parameters as discussed above. However, they depend on the flow rates to the individual burner passages which could not be measured using the instrumentation available at WIPCO. Consequently, a means was devised of measuring each flow rate by sensing the pressure differential across a restriction in the burner passage. For the secondary air passages, the differential of pressure across the sliding sleeves and perforated plates was measured (a total of eight flow rate measurements). For the core air, the pressure drop across the butterfly control valve was measured (a total of four flow rate measurements). The upper nine tertiary air ports were controlled by a rotating sleeve similar to the air flow control device on a Bunson burner. The pressure drop across each control element was measured (a total of nine flow rates). The lower tertiary air ports (four) were controlled by a single sliding damper which restricted the open area of the perforated plate. The pressure drop across the damper/perforated plate combination was measured (one flow rate only). Megahelic differential pressure gauges were installed outside the windbox so that the pressure drops could be measured from the firing floor during operation. Each of these internal flow meters was calibrated in the LWS test facility by direct measurement of air flow rate (via calibrated Venturis) and differential pressure under typical operating conditions. The flow meter designs and calibration procedures are discussed in Appendix D of Volume 2.

One important limitation of these internal flow meters is that the area of the flow sensing elements vary with the control positions. This requires a separate calibration curve for each control position. To measure flow rate accurately, it is necessary to measure the differential pressure accurately and to select the appropriate calibration curve based on the known control position. The calibrations discussed in Appendix D of Volume 2 were developed by calibrating the pressure drop versus flow rate at several discreet control positions and then developing the general relationship to interpolate between positions. During the tests at WIPCO there was always some question as to the exact position of the control elements. Prior to the tests and at scheduled outages during the tests, the relationships between control indications and actual control positions were measured directly. In some cases, lost motion in the linkages or component warping (especially the sliding sleeves) contributed to inaccuracy.

Based on these factors, the accuracy of the internal flow meters was probably in the range of ± 5 percent at best. While this is reasonable accuracy for such a system, it should be noted that a ± 5 percent range in burner zone stoichiometry corresponds to a variation in NO_x emissions at zero percent O_2 of about 80 ppm based on the prototype burner tests in the new LWS. Thus, the internal flow meters could be used as approximate indications of burner zone stoichiometry or burner balance only. The final adjustments to ensure burner balance were made by monitoring the excess O_2 and CO emissions at the sampling probe array upstream of the air heaters. Although the combustion products exiting the furnace passed through the convective pass and made two changes in direction prior to reaching the sampling location, stratification persisted. For unbalanced conditions, the oxygen concentration on one side of the duct was found to be up to 3 percent higher than on the other side. Under balanced conditions it was possible to produce a nearly constant excess O_2 distribution within about ± 0.25 percent.

The general procedure used to establish a low NO_x staged operating point involved a series of adjustments. Beginning with the tertiary air ports closed at a satisfactory unstaged operating point (actually a burner zone stoichiometry of about 100 percent TA), the excess O_2 was increased so that subsequent adjustments which provided increased restriction would not lower excess O_2 to the smoke point. Then the registers and core air valves were adjusted to approximately the desired settings for staged operation. The tertiary air ports were opened in steps to the full open position. Usually this produced a burner zone stoichiometry in the range of 85 percent TA. The sleeves were then partially closed to divert air from the burner throats to the tertiary air ports and thus reduce the burner zone stoichiometry. This procedure required care to avoid burner imbalance. Usually, the controls on each burner were adjusted in small steps two burners at a time to minimize imbalance. The final adjustments were to vary the burner settings for minimum imbalance and to lower the excess air to achieve the desired burner zone stoichiometry.

4.4. Effects of Operating Parameters

An extensive series of optimization tests were conducted under staged conditions. These tests evaluated the DMB system over a range of operating parameters that included:

- Burner controls
- Burner zone stoichiometry
- Overall Stoichiometry (Excess Air)

4.4.1 Balancing of Burner Controls

The DMB system installed at the WIPCO boiler incorporated a number of burner controls to provide considerable flexibility in optimizing burner performance. The tapered design of annular coal nozzle is movable and, thus, varies exit area and velocity. Combustion air is supplied to the burners and tertiary air ports from a common windbox. The two concentric secondary air passages for each burner are equipped with adjustable registers for swirl control and axially-movable sleeves for flow control. The air flow to the central passage of each burner, termed the core, is controlled with a butterfly valve. Thus, for each of the four burners, there was a total of 6 variables, not including the tertiary air ports. A detailed parametric test matrix of just three positions for each of the 24 available burner variables would result in 2.82×10^6 test conditions. Since this was clearly impractical, a simpler approach was taken. First, the performance trends for each variable were accessed. Generally, this involved making adjustments to all four burners or the upper or lower burner pairs simultaneously. The intent was to minimize any horizontal imbalance since such imbalance can degrade performance significantly as was discussed in Section 4.1. Second, the data were used to adjust flame shape, burner zone stoichiometry and burner balance by making perturbations in baseline operating conditions.

The following paragraphs discuss the impacts of burner adjustments on performance. For clarity, the effects of each parameter are shown separately. In the figures, separate symbols joined by solid lines are used to designate sets of operating conditions for all adjustments except for the parameter of interest which are held constant. In some cases, the effects of changing a parameter were dependent on the other operating conditions.

Moving the burner coal nozzles varied the primary velocity and influenced flame characteristics and emissions. At high primary velocities (achieved with the nozzles pushed in toward the furnace) flame standoff generally increased. NO_x emissions generally decreased for higher primary velocities, as shown in Figure 4-18. However, apparent flame stability as well as combustion efficiency (indicated by increased CO levels) also decreased. Adjustments of available burner variables, including register position and core air flowrate, were necessary to improved flame characteristics and CO emissions. These adjustments resulted in increased NO_x emission and shorter flame standoff distance.

The effects of inner and outer secondary register position are shown in Figures 4-19 and 4-20, respectively. In general, opening the inner registers tended to decrease the NO_x emissions with little effect on CO levels. Opening the inner registers decreased swirl but increased the amount of air passing through the inner secondary passage. The higher air flow rate resulted in a higher secondary air velocity and burner zone stoichiometry. Since NO_x emissions increased as burner zone stoichiometry increased the major impact was on fuel/air mixing at the base of the flame. The outer secondary air registers had a greater effect on performance, primarily because of the larger air flow change. Closing the outer registers tended to decrease NO_x emissions by decreasing the flow through the outer secondary air passage and thus decreasing burner zone stoichiometry. The effect on combustion efficiency as indicated by CO levels was mixed and dependent on the other burner settings.

All Nozzles Adjusted Equally

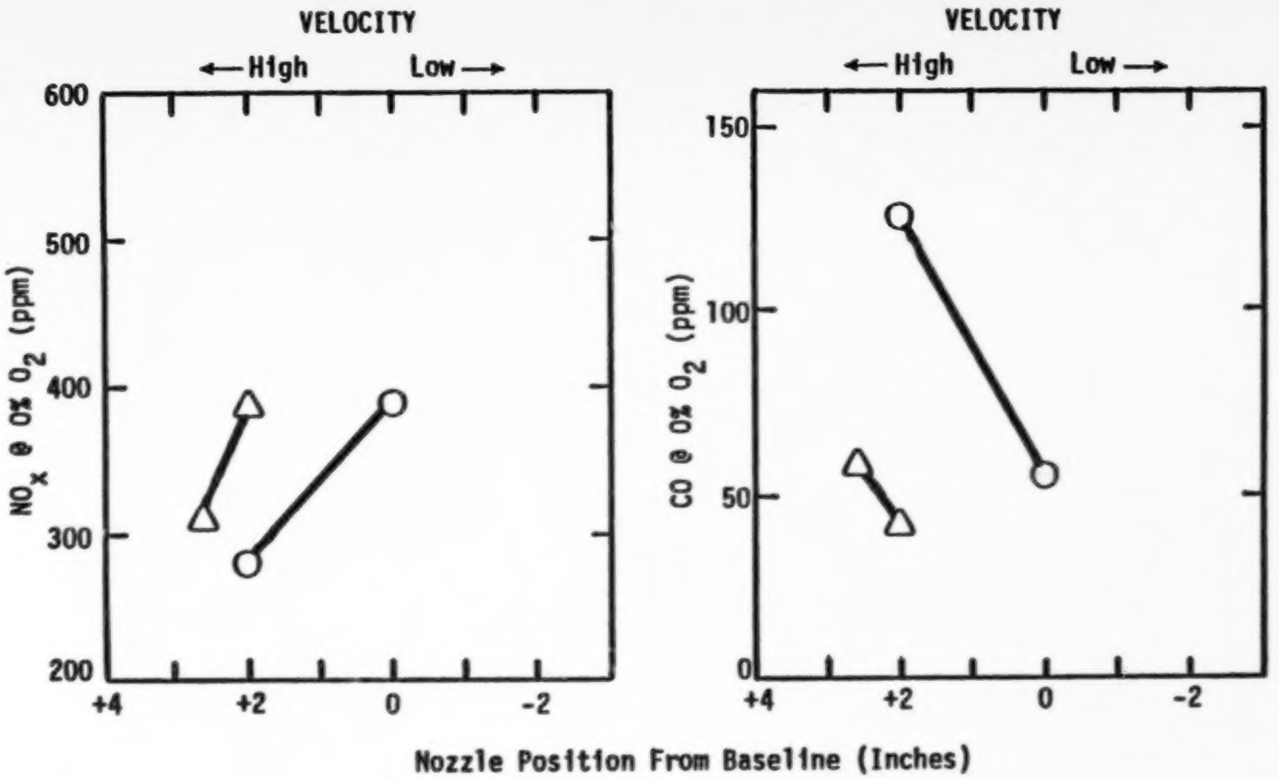


Figure 4-18. Effect of coal nozzle position on staged performance.

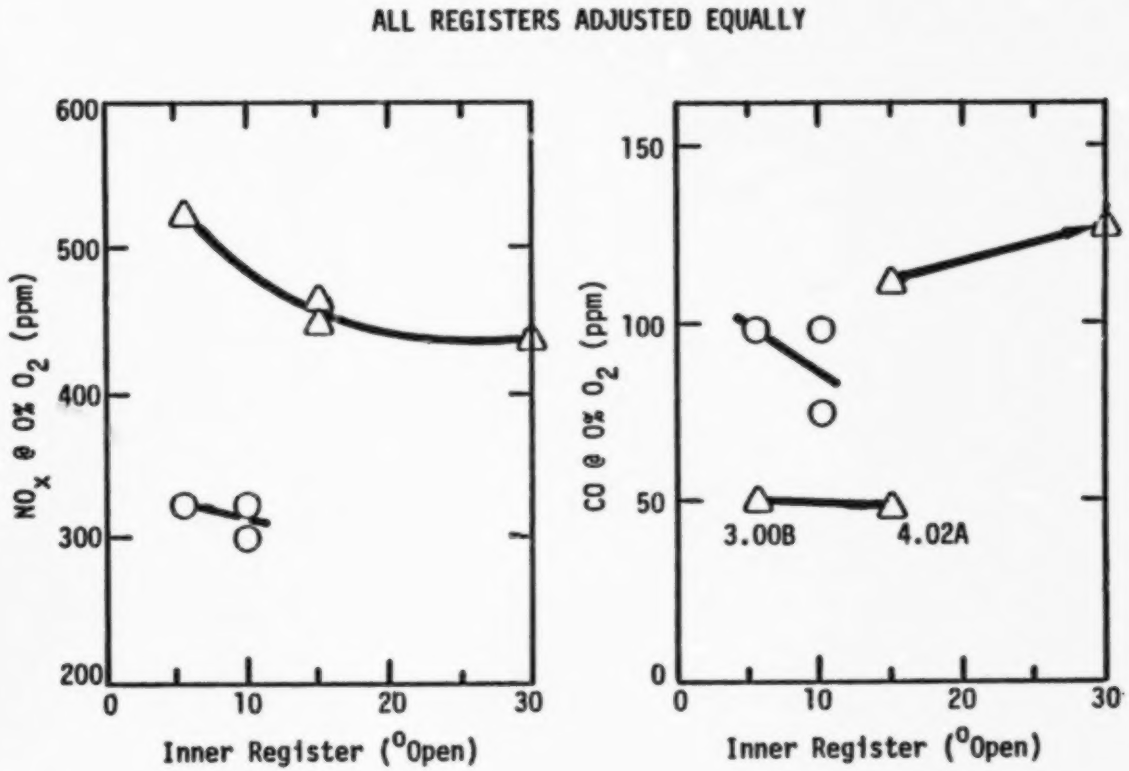


Figure 4-19. Effect of inner register adjustment on staged performance at WIPCO.

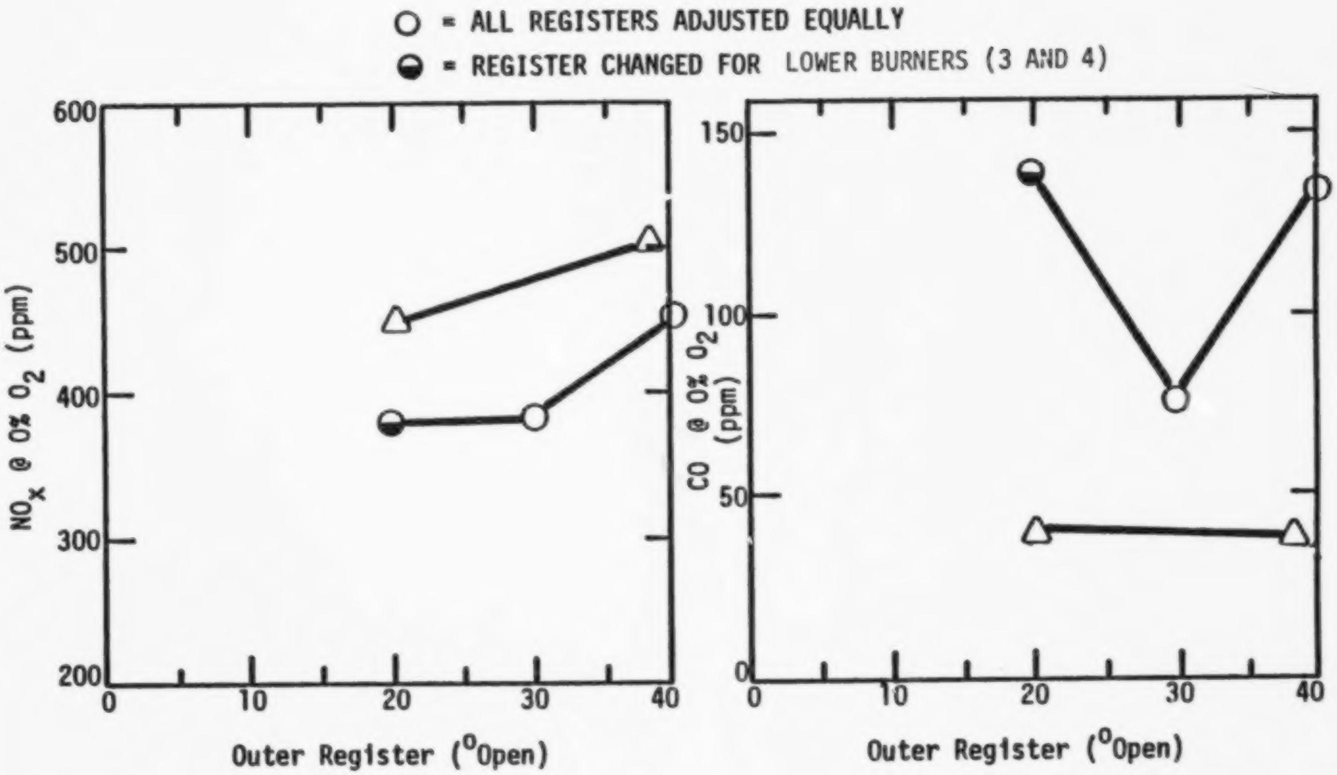


Figure 4-20. Effect of outer register adjustment on staged performance at WIPCO.

The sleeves control the air flow through the secondary air passages but do not impact swirl. The effect of the sleeves on the air flow rates depends on the importance of the pressure drop across the sleeves to the total pressure drop between the windbox and furnace, which includes the pressure drops across the sleeves, registers and exits. Thus, for conditions with the registers substantially open the sleeves were very effective in controlling flow. However, as the registers approached the fully closed positions, the sleeves were much less effective. Closing both sets of sleeves uniformly, decreased the air flow rates to the secondary air passages and reduced burner zone stoichiometry. However, adjustment of a smaller number of sleeves served mainly to re-distribute the air flow rates among the burner passages with little impact on burner zone stoichiometries. These factors complicate the interpretation of the effects of sleeve position changes. Figures 4-21 and 4-22 show the effects of inner and outer sleeve adjustments respectively. Closing all four inner registers from 50 to 25 percent open decreased NO_x over 100 ppm for the conditions shown in Figure 4-21. Figure 4-22 shows data from a series of tests in which the outer sleeves for the top two burners (1 and 2) were closed to divert more air to the lower burners. Because of the size of the sleeves there was little effect on emissions when the two sleeves were closed from 100 to 25 percent open. In another test, closing the sleeves from to 20 percent open to fully closed had a greater effect, decreasing NO_x by 50 ppm for the conditions shown.

The flow of air through the burner core affected the operation of the pilot oil flame and the shape of the coal flame. Due to the positioning of the oil nozzle, the core provided the major supply of combustion air to the base of the pilot flame. The operators often adjusted the core air valve to provide for easy ignition of the pilot flame and acceptable pilot flame stability. During coal fired operation, the core air flow rate is small compared to the secondary air flow rate. However, variations in the core air flow rate never the less impacted flame characteristics. With no or very low core air flow, the core air passage forms a wake. As the flow rate is increased, the shape of the recirculation zone changes. Generally, increasing core air flow rate moved the base of the flame further into the furnace. Another important function of the core air flow is to cool the

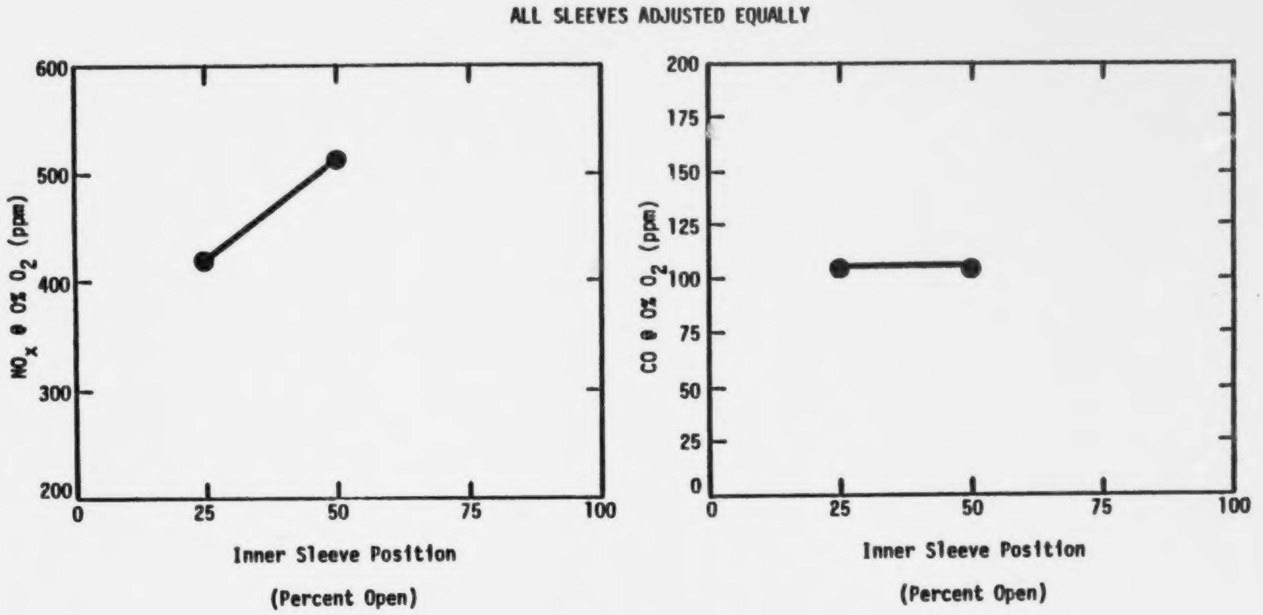

ALL SLEEVES ADJUSTED EQUALLY

Figure 4-21. Effect of inner sleeve position on staged performance.

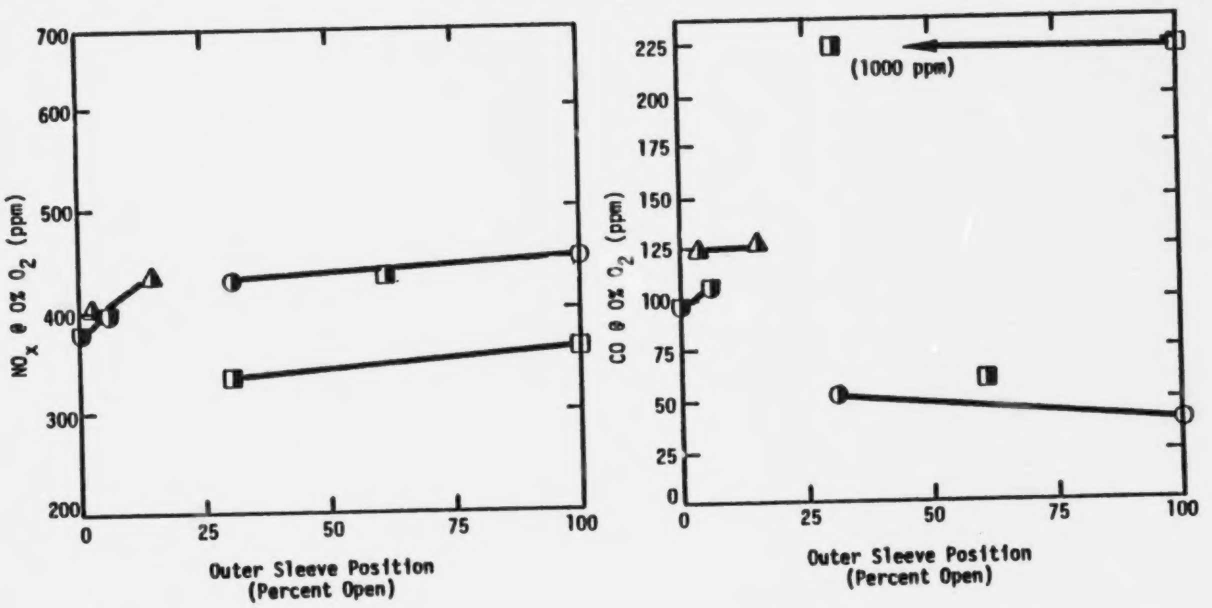


Figure 4-22. Effect of outer sleeve position for burners 1 and 2 on staged performance.

ignition components when they are out of service and to prevent accumulation of pulverized coal in the burner. For these reasons, the operators considered operation with the core air valves more than 45° closed to be unacceptable. Figure 4-23 shows typical effects of the core air valves on emissions. The effects were mixed.

Individual control of each tertiary air port permitted evaluation of extended substoichiometric regions and biasing of air flow vertically and horizontally. Lowest NO_x emissions were achieved with all tertiary air ports fully open. Attempts to bias the tertiary air flow distribution by closing selected ports generally resulted in increased NO_x emissions due to the increase in burner zone stoichiometry. Low windbox to furnace differential pressure did not provide sufficient driving force to push air through closed or partially closed tertiary air ports.

In summary, a range of burner settings were identified that achieved low NO_x emissions at WIPCO during the short term optimization tests. These settings are summarized in Table 4-5. The lowest NO_x emissions were achieved with the internal windbox controls set to minimize air flow through the burner throat and divert the maximum amount through the tertiary air ports. The results from the optimization tests at WIPCO also indicated that low NO_x emissions would be achieved with a high primary air velocity still consistent with a stable flame. Table 4-5 also includes the burner settings producing optimum performance during the tests of the prototype burner in the LWS. The WIPCO and LWS settings were similar. The differences were primarily related to the need to balance burners and restrict air flow through the throat to achieve low burner zone stoichiometries.

4.4.2 Effects of Combustion Stoichiometry on Emissions and Combustion Efficiency

The effects of the burner controls discussed in the previous section included the combined effects on individual burner performance and burner zone stoichiometry. As discussed previously, it was not possible to vary burner zone stoichiometry separately as was done in the prototype DMB tests

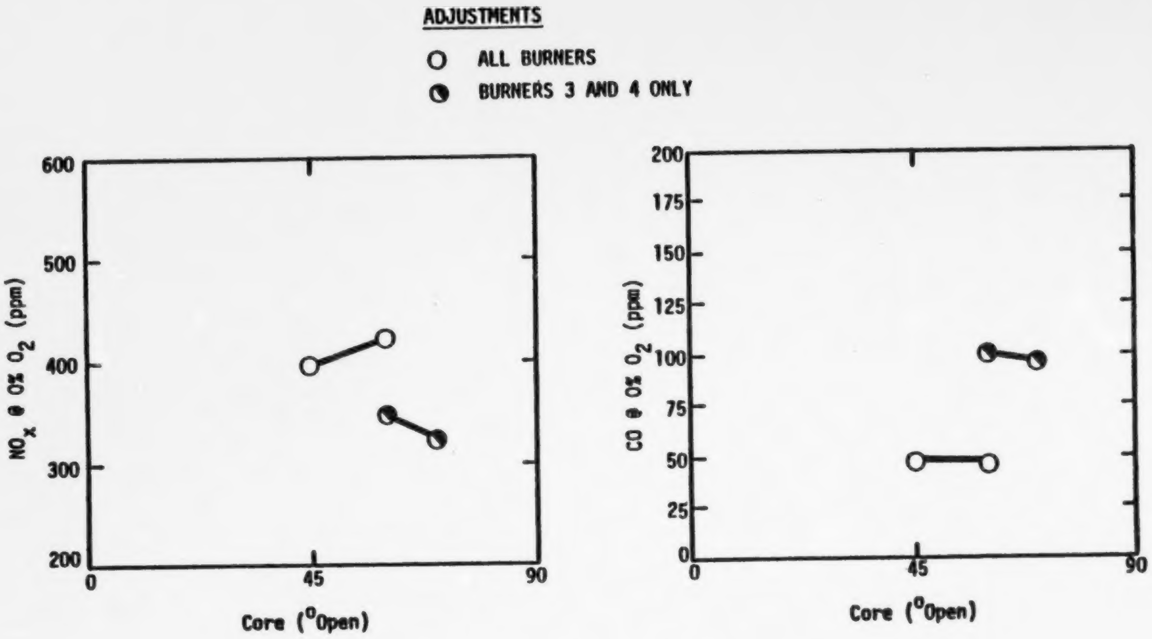


Figure 4-23. Effect of core air valve position on staged performance.

TABLE 4-5. RANGE OF BURNER SETTINGS FOR LOWEST NO_x AT WIPCO

PARAMETER	EFFECT OF OPENING ON:		SETTINGS FOR LOWEST NO_x	
	BURNER OPERATION	NO_x	WIPCO	LWS
INNER REGISTER	Higher Secondary Velocity Higher SR_B Lower Swirl	↓	5-18° open	15° open
INNER SLEEVE	Higher Secondary Velocity Higher SR_B	↓	12-50% open	Full Open (SR_B controlled independently)
OUTER REGISTER	Higher Secondary Velocity Higher SR_B Lower Swirl	↓	9-35° open	15° open
OUTER SLEEVE	Higher Secondary Velocity Higher SR_B	↓	0-50% open	Full Open (SR_B controlled independently)
NOZZLE (INSERTION)	Higher Primary Velocity	↓	Zero and inserted 2.0 inches	Zero
Core Air Valve	Higher SR_B	Mixed	60-90° open	45° open
TERTIARY AIR PORTS	Higher Tertiary Velocity Lower SR_B	↓	Full Open	Full Open

in the LWS. However, a cross plot of the WIPCO data can illustrate the effects of burner zone stoichiometry and excess air as shown in Figure 4-24. It should be noted that these data were not obtained at fixed burner settings and thus are not strictly comparable to the prototype burner data plots in Section 3.0.

The data in Figure 4-24 are plotted for two ranges of excess air. For each range, NO_x emissions decreased as burner zone stoichiometry decreased (as expected). The lower range of excess air resulted in lower NO_x emissions and somewhat higher CO emissions, again as expected. Note that the apparent data scatter is much greater for CO emissions than for NO_x emissions. This is due primarily to burner imbalance for the various test conditions. As was discussed in Section 4.3, burner imbalance has no impact on NO_x emissions but a marked impact on CO emissions especially at low burner zone stoichiometries near the knee of the CO curve.

As a preliminary indication of combustion efficiency, fly ash samples were obtained from the multiclone hopper and analyzed for carbon content. A carbon utilization efficiency was calculated based on the ratios of carbon to ash in the coal and fly ash samples. This is equivalent to using coal ash as a tracer. The results are correlated with CO emissions in Figure 4-25. It should be noted that the carbon content of the fly ash and the calculated carbon utilization efficiencies are not true indications of combustion efficiency. Subsection 4.7 discusses the impacts of the DMB on overall boiler performance including combustion efficiency.

4.5 Minimum NO_x Emissions

The large number of burner controls on the WIPCO DMB installation allowed the DMBs to be set up to produce a wide range of flow conditions and emissions. Minimum emissions were produced by adjusting the burners to achieve the following:

- Short flame standoff distance
- Low burner zone stoichiometry

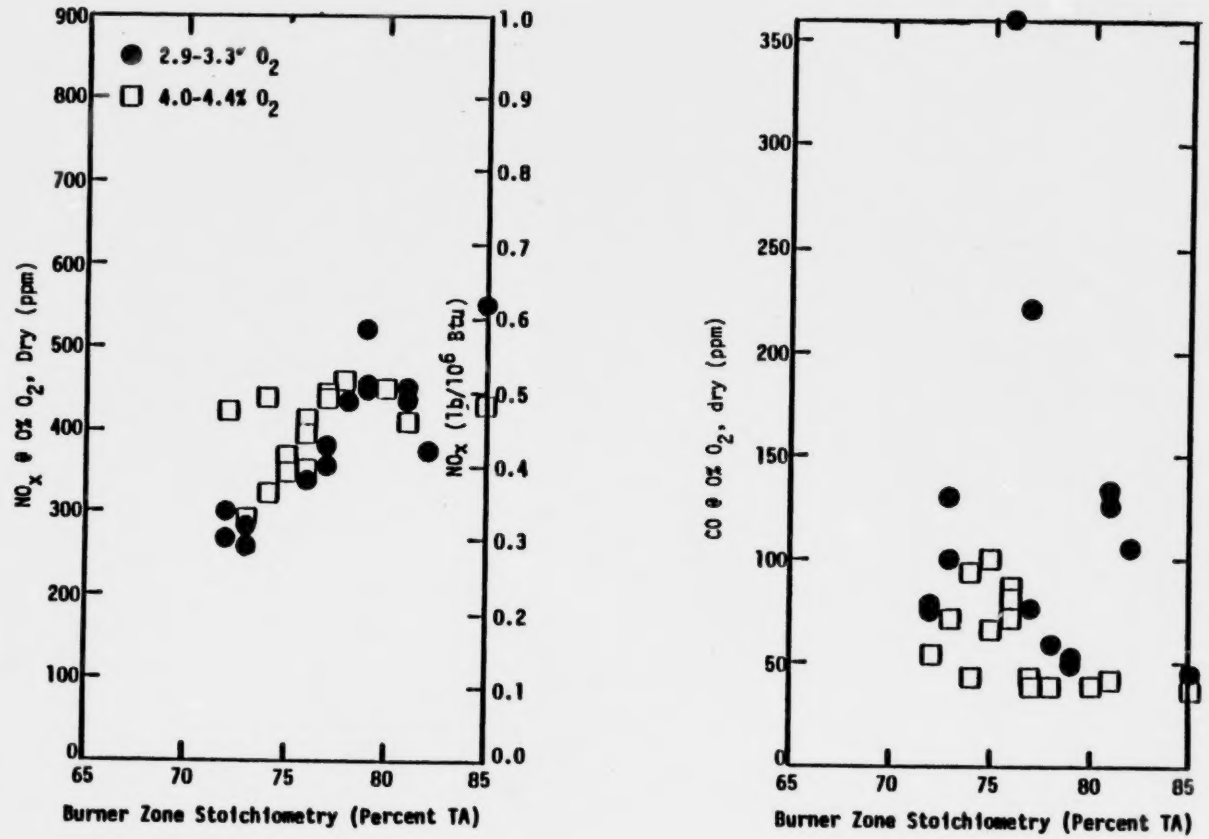


Figure 4-24. Effect of burner zone stoichiometry on emission at WIPCO.

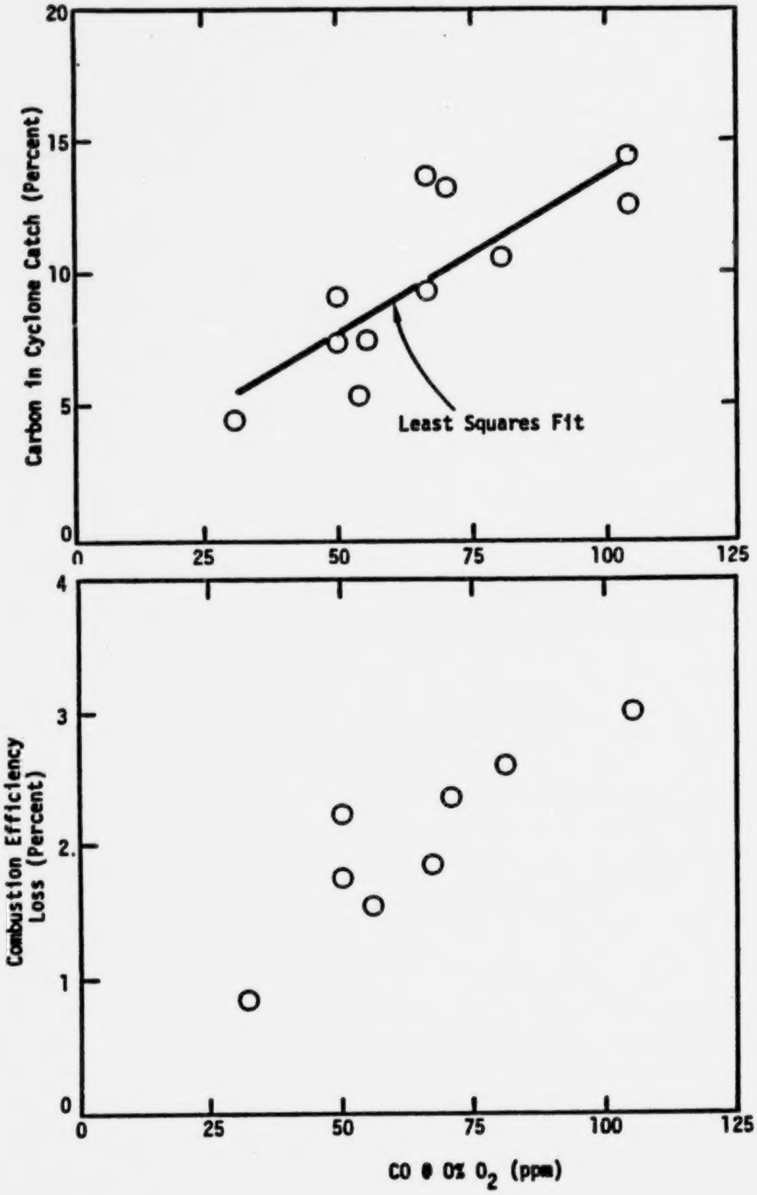


Figure 4-25. Correlation of combustion efficiency with CO.

- Balanced burners

These conditions could be achieved with several combinations of burner settings. Table 4-6 lists 14 tests where NO_x emissions were 0.35 lb/10^6 Btu or less. These were short term tests where the unit operated at the specified conditions for periods on the order of a few hours after achieving equilibrium.

Close examination of Table 4-6 shows that low NO_x emissions were obtained for a range of burner settings. However, for all conditions the registers and sleeves were substantially closed. This was required to direct enough air to the tertiary ports so as to produce low burner zone stoichiometries.

The burner zone stoichiometries for these conditions were in the range of 72 to 77 percent TA. However, excess O_2 covered a fairly wide range: 2.87-3.94 percent.

The low NO_x operating conditions listed in Table 4-6 were obtained over a 5-month period and represent the best operating conditions achievable on each date. In many cases, it was found that the conditions which produced optimum performance on one day would produce unacceptable performance on subsequent days usually characterized by unacceptable flame shapes or burner imbalance as indicated by O_2 and CO stratification measured upstream of the air heater. This was a key problem limiting operation for extended periods with low NO_x emissions. The following reasons for the observed performance were considered:

1. Inability to duplicate burner settings.
2. Low windbox-to-furnace pressure differential.
3. Coal variations.
4. Pulverizer performance variations.
5. Furnace/ash build up.
6. Non-uniform tertiary air entrainment

TABLE 4-6. SUMMARY OF TEST CONDITIONS WHICH PRODUCED NO_x EMISSIONS LESS THAN 0.35 LB/10^6 BTU

DATE	TEST NO.	LOAD (MW)	SR_b (%TA)	SR_t (%TA)	EMISSIONS			BURNER SETTINGS															
					O_2 (%)	NO_x ppm (@0%O_2)	CO ppm (@0%O_2)	NOZZLE (In from BL)				CORE AIR VALVE (°Open)				REGISTERS IN/OUT (°Open)				SLEEVES IN/OUT (°Open)			
								1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
3/7/83	24.01	20.02	72	115	2.87	279	194	0	+0.5	0	0	90	90	60	60	15/24	15/20	15/35	15/20	20/12	12/6	50/50	50/12
3/9/83	25.01	19.9	73	118	3.26	286	99	0	+0.5	0	0	60	60	70	70	5/24	5/20	5/35	5/20	19/0	12/0	50/38	50/12
3/9/83	25.02	20.0	73	118	3.22	259	130	0	+0.5	0	0	60	60	70	70	5/24	5/20	5/35	5/20	19/0	12/0	50/38	50/12
3/9/83	25.03	20.0	72	117	3.18	268	79	0	+0.5	0	0	60	60	70	70	5/24	5/20	5/35	5/20	19/0	12/0	50/38	50/12
3/10/83	26.02	20.0	73	118	3.33	265	163	0	+0.5	0	0	60	60	70	70	5/24	5/20	5/35	5/20	19/0	12/0	50/38	50/12
3/11/83	27.02	20.1	74	119	3.47	293	105	0	+0.5	0	0	60	60	70	70	5/21	5/20	5/35	7/20	19/0	12/0	50/38	50/12
3/12/83	28.01	20.2	72	118	3.25	302	75	0	0	0	0	60	60	70	70	5/24	5/20	5/35	5/20	19/0	12/0	50/38	50/12
3/15/83	29.01	20.0	76	121	3.68	297	74	0	0	0	0	60	60	70	70	15/25	5/20	18/35	5/20	50/25	12/50	50/38	50/12
5/5/83	34.01	20.2	74	122	3.91	301	75	0	0	0	0	60	60	70	70	10/15	10/10	10/25	10/10	19/0	12/0	38/19	25/0
5/5/83	34.02	20.2	70	120	3.56	282	96	0	0	0	0	60	60	70	70	10/15	10/10	10/25	10/10	19/0	12/0	38/19	25/0
5/7/83	35.01	20.0	72	122	3.81	308	84	0	0	0	0	60	60	70	70	10/15	10/10	10/25	10/10	19/0	12/0	38/19	25/0
5/9/83	36.01	20.1	73	123	4.07	294	71	0	0	0	0	60	60	70	70	9/15	11/10	10/25	10/9	19/0	12/0	38/19	25/0
5/17/83	39.01	19.7	73	120	3.60	270	81	0	0	0	0	60	60	60	60	10/25	10/10	10/25	10/10	19/0	12/0	50/38	50/12
8/19/83	46.01	19.5	77	123	3.94	289	74	+2 3/4	+2 1/2	+2 5/8	+2 3/8	60	60	60	60	10/10	10/10	10/15	10/15	50/50	50/50	50/50	50/50

During much of the testing the burners were returned to unstaged operating conditions at the end of each testing day. Thus, the changes in performance observed could have been due to lack of precision in setting the burners. The controls for each register and tertiary air port had substantial hysteresis. The linkages joining the electric drives to the actual controls inside the windbox were installed with large tolerances to compensate for thermal expansion at normal windbox temperatures (500-600°F). These large tolerances resulted in substantial lost motion in the linkages. To compensate for the lost motion, the relationship between registered vane position and drive indication were measured after making adjustments in both directions. The resulting hysteresis curves were used throughout the testing program to ensure that the register settings were known as accurately as possible. The construction of the secondary air sleeves was of some concern also. Each sleeve was suspended from a single point at the top. During most of the testing, the sleeves were misaligned and partially blocked each register even when fully opened. Although the sleeves were calibrated and checked repeatedly at outages, the actual positions of the sleeves were in question since the sleeves could be visually checked only when the unit was shutdown. Air flow through the windbox and normal vibration resulted in movement of the sleeves. It is normal practice for Foster Wheeler to tack weld the sleeves in fixed positions following optimization tests. For example, after the unstaged tests conducted by Foster Wheeler (discussed in Appendix A),the sleeves were welded in the fully open position. Misalignment of the sleeves could have resulted in two problems: First, the secondary air flows may have been non-uniformed around the circumference of the burner and second, the air flow versus pressure drop and sleeve position calibrations may have been inaccurate. The effect of cocked sleeves on single burner performance was evaluated during the test of the final prototype DMB in the new LWS and were discussed in Section 3.5. Briefly, cockes sleeved had no measurable impact on burner performance. However, cocked sleeves could impact burner balance.

For most of the low NO_x operating conditions, the windbox to furnace pressure differential was in the range of 1.5 - 2.0 in. H_2O. This is low compared to the Intervane burner design point, 3.5 in. H_2O. Due to this low differential pressure, variations in air flow patterns in the windbox may have impacted the flows through some burner passages. For example, a change in coal moisture would change the amount of windbox air withdrawn to the pulverizers. If the flow rates to both pulverizers changed by the same amount, the effect would be a vertical imbalance in the air supplied to the upper and lower burners. If the flow rate to only one pulverizer changed, both horizontal and vertical imbalance could result. While it is possible that low windbox to furnace pressure differential contributed to flow imbalance problems, the effect was probably minor. Static pressure measurements throughout the windbox from the upper tertiary air ports to the area below the lower burners indicated uniform static pressure under all test conditions.

Coal variations could have contributed to variations in performance also. Throughout the testing period WIPCO purchased coal on the spot market. Thus, the coal composition was changing continually. Appendix C of Volume 2 lists the compositions of samples analyzed throughout the testing period. These variations may have affected flame stability, NO_x emissions and carbon burnout.

It is well known that coal fineness can impact burner performance including flame stability, combustion efficiency and even slagging. During the prototype burner tests in the LWS, a reduction in fineness to less than 65 percent through 200 mesh resulted in flame stability problems (See Section 3.5). At WIPCO the operators normally adjust the pulverizers to produce a pulverizer pressure drop meeting a Foster Wheeler specification. This is achieved by adjusting the classifiers. No fineness measurements are made. During the test program, several fineness measurement tests were conducted to evaluate pulverizer performance. The results in Table 4-7 show that in many cases fineness was less than the nominal specification (70 percent through 200 mesh). Some of the variations in performance may have been due to this poor coal fineness. It should be noted that the classifier settings listed in Table 4-7 are indicated only. The lost motion in the indicator linkage has not been taken into account. According to the operators, this is substantial.

TABLE 4-7. FINENESS TESTS AT WIPCO

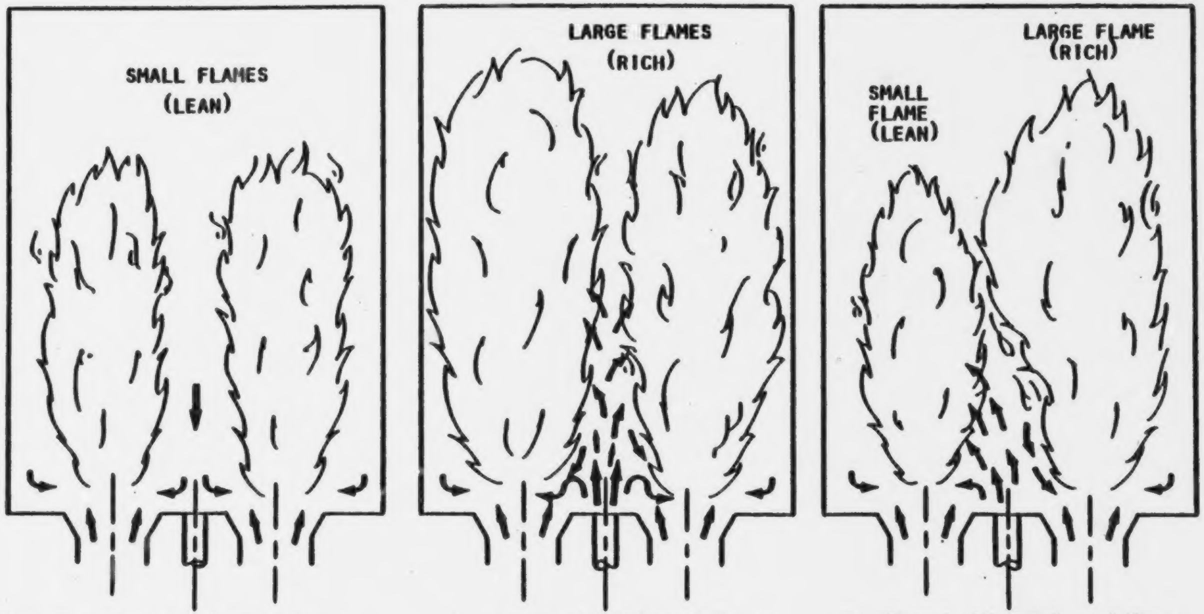
	MILL A				MILL B			
DATE	CLASSIFER SETTING	WT % THROUGH MESH		BURNER #1 BURNER #2	CLASSIFIER SETTING	WT % THROUGH MESH		BURNER #3 BURNER #4
		50	100	200		50	100	200
2/22/83	50%	99.6 99.8	95.4 94.2	71.4 70.4	46%	99.8 99.8	93.4 92.4	64.6 64.8
3/16/83	50%	99.4 99.6	95.8 94.4	72.4 68.6	39%	99.4 99.6	99.4 94.8	69.0 71.0
6/24/83	40.5%	99.8 99.8	96.4 96.2	62.9 59.6	40.5%	99.8 99.8	93.2 94.0	61.0 59.6
9/15/83	48%	- -	- -	68.7 64.6	32%	- -	- -	68.9 67.2

The WIPCO furnace has wall soot blowers to control furnace wall ash accumulation. Also, the operators poke at slag deposits above burner throat openings, know as "eyebrows", once per shift or as required to minimize build up. The normal operating procedure is to cycle the wall blowers as well as the retractable soot blowers in the convective pass and air heater during two of the three daily shifts. With a clean furnace, the design point steam temperature cannot be achieved. Consequently, the ash deposits are allowed to grow to the point where a very slight amount of attemperation is required to maintain steam temperature at design point. Then, one of the wall blowers will be operated during the normal soot blowing period. The wall blower to be operated is selected based on experience by cycling through all of the wall blowers in the furnace. An attempt was made to correlate burner performance with observed furnace conditions, steam temperatures and soot blowing frequency. No systematic trends could be found.

While these factors undoubtedly contributed to the performance variations, the major imbalance problems were probably related to mixing patterns within the furnace. This is based on the results of several tests where significant changes and performance occurred over short time periods with no apparent changes in operating conditions. For example, in one test, a low NO_x operating conditions was established with a fairly high windbox to furnace pressure differential. A stratification test indicated that the burners were well balanced. The excess O_2 on the south side of the unit was about 0.5 percent higher than on the north side. To achieve this balanced condition, it was necessary to close the outer sleeves on the south side burners much more than on the north side burners. The operators ran the unit with these settings over night making only small changes to the register settings. Based on the hysteresis curves, these changes did not impact the actual register vane positions. The next morning, the stratification test was repeated. The result was 3.0 percent O_2 higher on the north side of the unit. The internal flow meters showed the same distribution for both tests. To restore balanced conditions, it was necessary to open the outer sleeves fully.

An isothermal flow study was conducted to evaluate the mixing patterns produced by DMBs with shared tertiary air ports. The modeling approach and test results were discussed in subsection 3.7. These tests showed that imbalance in the flow from the burners caused the tertiary air to be preferentially entrained into the higher flow burner streams.

Based on all available data, this type of change in burner performance and balance is probably due to non-uniform mixing of tertiary air into the four flames. The close burner to burner spacing, shared tertiary air ports and low tertiary air momentum made the system overly sensitive to burner imbalance. This is illustrated in Figure 4-26. The typical performance under unstaged conditions is shown in Figure 4-26A. The unstaged flames are relatively small and operate independently. The recirculation within the flames entrains flow from along the firing face. This results in an inward flow direction directly between the burners. Figure 4-26B illustrates operation under ideal staged conditions. Since the flames are sub-stoichiometric, they are larger than the unstaged flames. They may be wider at the base also due to the high swirl. Ideally, the flow from the tertiary air port between the burners will mix uniformly with both flames following the DMB concept. This pattern was observed in the isothermal tests for balanced burner flows and high tertiary air momentum. However, the flow from the tertiary air port is in a direction opposite to the flow without the port. For some conditions, the unbalanced flow illustrated in Figure 4-26C could occur. Here the air flow from the port between the burners is preferentially drawn into one of the flames. This increases the available oxygen in that flame reducing its size. The other flame operates at reduced stoichiometry with lower entrainment power. Under some conditions this unbalanced flow pattern may be more stable than the balanced flow pattern and the flow from the tertiary air port may switch between flames. This bistable flow could occur with the center port as shown or could occur with other ports or perhaps in combination with a coanda effect where the tertiary air flow becomes attached to the furnace wall. It is possible that switching between flow conditions could occur in response to changes in some input variables such as pulverized coal flow rate, load, excess O_2, etc. Section 3.7 discussed these effects in some detail.


SMALL FLAMES
(LEAN)
LARGE FLAMES
(RICH)
SMALL
FLAME
(LEAN)
LARGE FLAME
(RICH)

A. Unstaged with balanced flames

B. Staged with balanced flames

C. Staged with imbalanced flames

Figure 4-26. Tertiary air mixing patterns.

Due to these problems, it was not possible to operate at low NO_x conditions for extended time periods. To obtain longer term data, operating points were selected which were further from the knee of the CO curve. Thus, any bistable operation would not result in excessive CO emissions, low combustion efficiency or smoke.

4.6 Extended Staged Operation

The optimization testing of the DMB system installed at the WIPCO Pearl Station involved evaluating the effects of each of the available burner adjustments to establish the settings which produced the lowest NO_x emissions without adverse effects on boiler performance or an increase in other emissions. These tests were short in duration with test conditions maintained constant for no more than eight hours. To fully demonstrate DMB technology and to provide an evaluation of emissions and effects on boiler performance, the boiler was subjected to several extended test periods. Long term tests were conducted during the following periods:

- May 25 to June 29, 1984 -(Initial 30 day test)
- August 27 to September 28, 1983 - (Second 30 day test)
- December 8 to December 20, 1983
- January 13 to March 26, 1984

During these extended tests, the boiler was operated by plant personnel over the load range required by system electrical demand at burner settings specified by EER. EER monitored NO_x, CO, O_2 SO_2, and CO_2 emissions continuously, obtained control room data sheets to monitor boiler operation, and collected coal and ash samples. Particulate, SO_3, hydrocarbons, HCN, and NH_3 were measured at selected conditions. Foster Wheeler personnel performed a boiler efficiency test at full load during the initial 30 day test period.

4.6.1 Initial 30 Day Test Period

The objective of the initial extended test period, performed from May 25 to June 29, 1983, was to monitor boiler performance over a period long enough to identify any operation problems and to obtain operator comments. A single set of burner settings was selected to be maintained throughout the 30 day period. The optimum burner settings were selected as those settings which resulted in maximum staging as shown by minimum burner zone stoichiometry with acceptable flame shapes and a balanced distribution of combustion air to the burners. Acceptable flame shapes were defined as flames that provided stable scanner readings and that were compact, without impingement on the walls. Optimum burner settings for operation with both mills and all burners in service were selected from Test 41.01 conducted on May 19, 1983. Test condition 41.01 produced NO_x emissions of 0.42 $lb/10^6$ Btu with CO emissions of 44 ppm. Overall burner zone stoichiometry was 78 percent at a total stoichiometry of 119 percent. These burner settings resulted in a uniform distribution of air to the burners, indicated by a balanced O_2 level across the backpass. The burner settings are listed in Table 4-8 for normal full load operation. Normal unstaged settings, shown in Table 4-9, were used for single-mill operation.

4.6.1.1 Gaseous Emissions

Hourly averages of the gaseous emissions were calculated from the continuous monitoring data. The hourly averages were used to calculate overall 30-day averages and daily averages. Table 4-10 lists the overall averages of the gaseous emissions. These averages represent emissions over a wide range of boiler operating conditions utilized by the boiler operators to satisfy system generating requirements. Boiler load varied from 10 to 20.7 MW during the test period. The boiler utilized two burners only at loads below 13 MW and was operated with the tertiary air ports closed. Boiler excess O_2 ranged from 2.4 to 5.9 percent.

Figure 4-27 shows the daily averages of gaseous emissions and boiler load. Due to the system generating requirements related to the weather, the boiler was operated at reduced loads during the early portion of the test with the unit dropping to two-burner operation at night. During the latter portion of the test the boiler was operated at full-load during the day and only slightly reduced-load at night. Midway through the test period the CO

TABLE 4-8. INITIAL 30-DAY TEST BURNER SETTINGS FOR TWO-MILL, FOUR-BURNER OPERATION

BURNER VARIABLE	BURNER SETTING			
	Burner No.			
	1	2	3	4
Nozzle Position, In. from baseline	0	0	0	0
Core Air Valve, °Open	60	60	60	60
Inner Register, °Open	10	10	10	10
Outer Register, °Open	25	10	10	10
Inner Sleeves, % Open	19	12	50	50
Outer Sleeves, % Open	50	0	38	12

NO_x Ports	1A	2A	3A	4A	Outer	Bottom	Center
% Open	100	67	33	0	100	100	100

TABLE 4-9. 30-DAY TEST BURNER SETTING FOR SINGLE-MILL, TWO-BURNER OPERATION

Burner Variable	Burner Setting	
	Burners in Service	Burners Out of Service
Core Air Valve, °Open	90	40
Inner Register, °Open	10	0
Outer Register, °Open	25	0
Inner Sleeves	Sleeves at Same Settings as Two-Mill Operation	
Outer Sleeves		
NO_x Ports, % Open	All 0% Open	

TABLE 4-10. INITIAL 30-DAY TEST AVERAGE OF GASEOUS EMISSIONS

Species	Average Concentration		
	Measured	Corrected to 0% O_2	lbs/10^6 Btu
NO_x	350 ppm	432 ppm	0.50
CO	69 ppm	85 ppm	0.060
SO_2	2981 ppm	3682 ppm	5.98
CO_2	14.8%	18.3%	204.2
O_2	4.0%	---	---

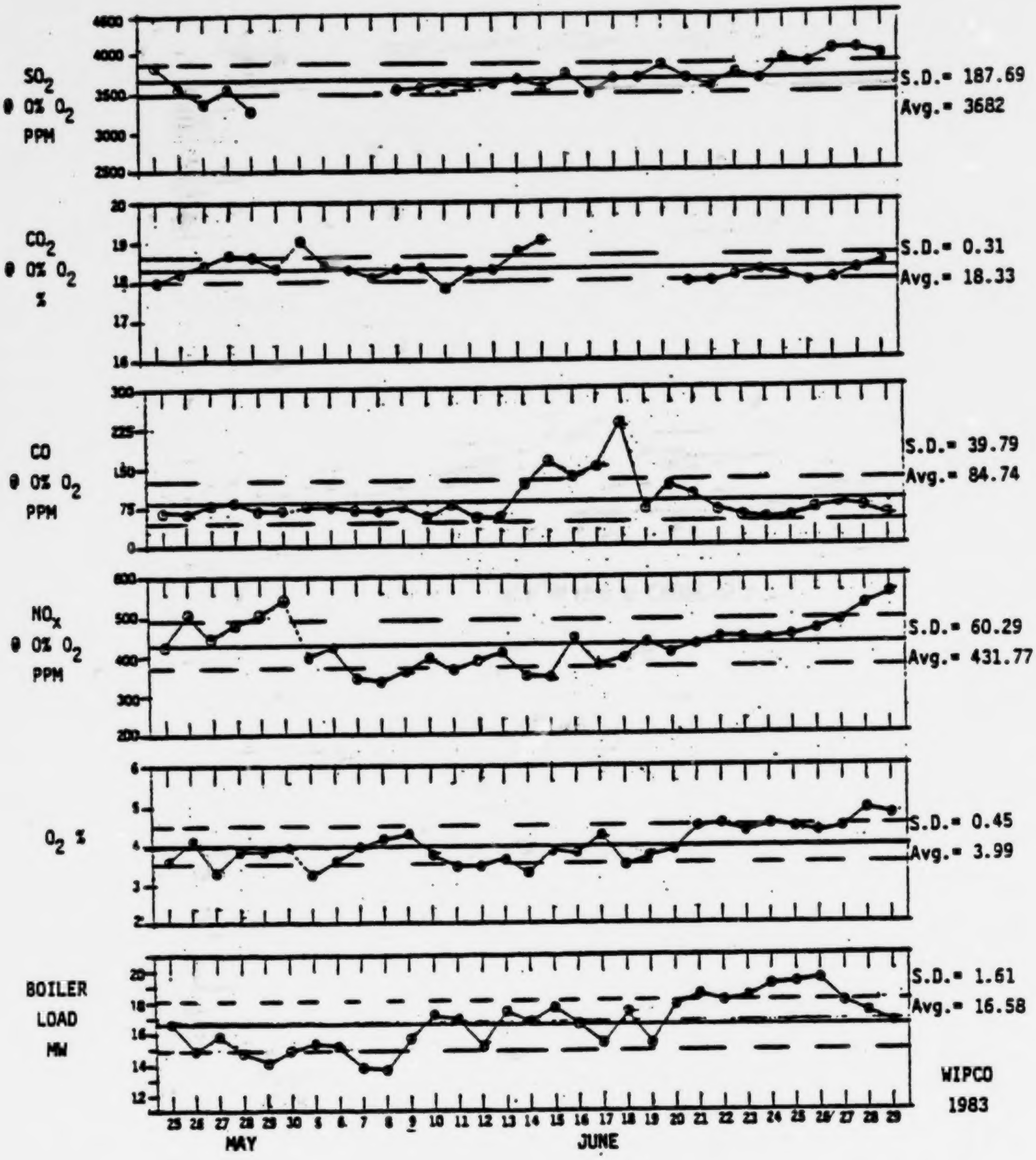


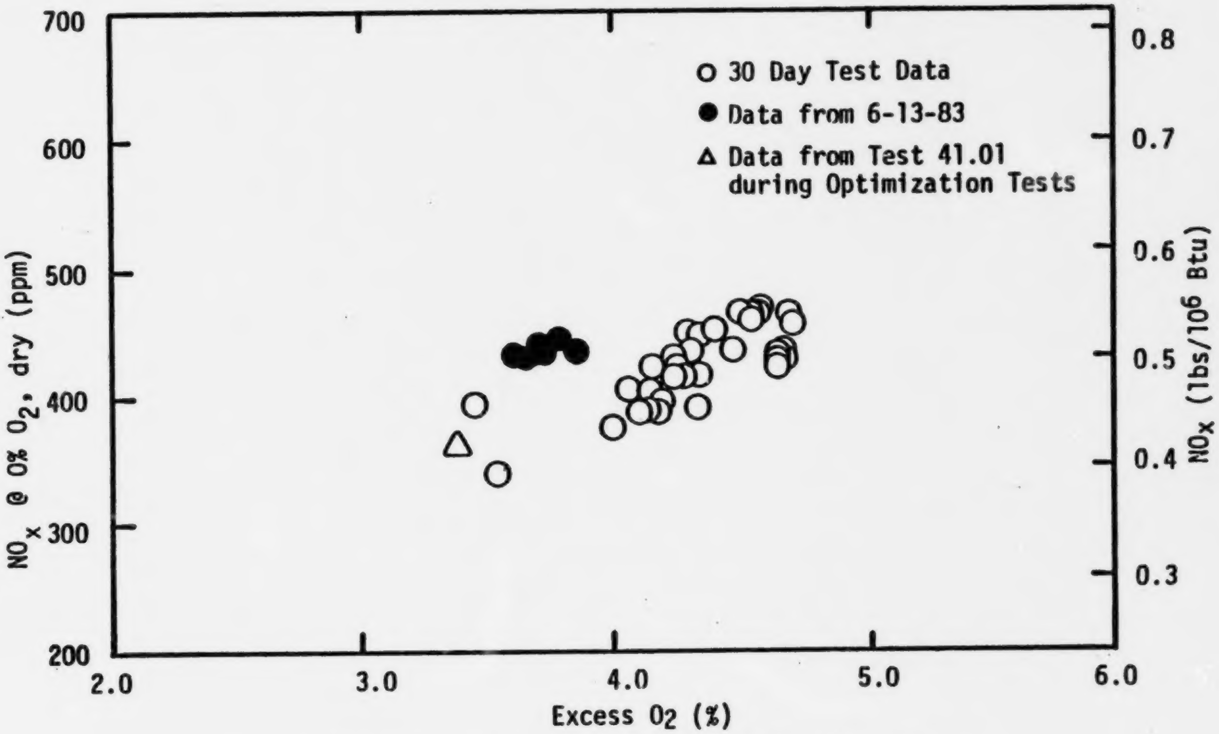
Figure 4-27. Daily averages of gaseous emissions during initial 30-day test.

emission levels increased significantly. The O_2 level was increased by the operators to reduce the CO emissions without changing the burner settings. The increase in O_2 resulted in a corresponding increase in NO_x emissions. The CO_2 and SO_2 emissions are directly related to the coal composition and did not vary significantly during the test.

4.6.1.2 NO_x Emissions

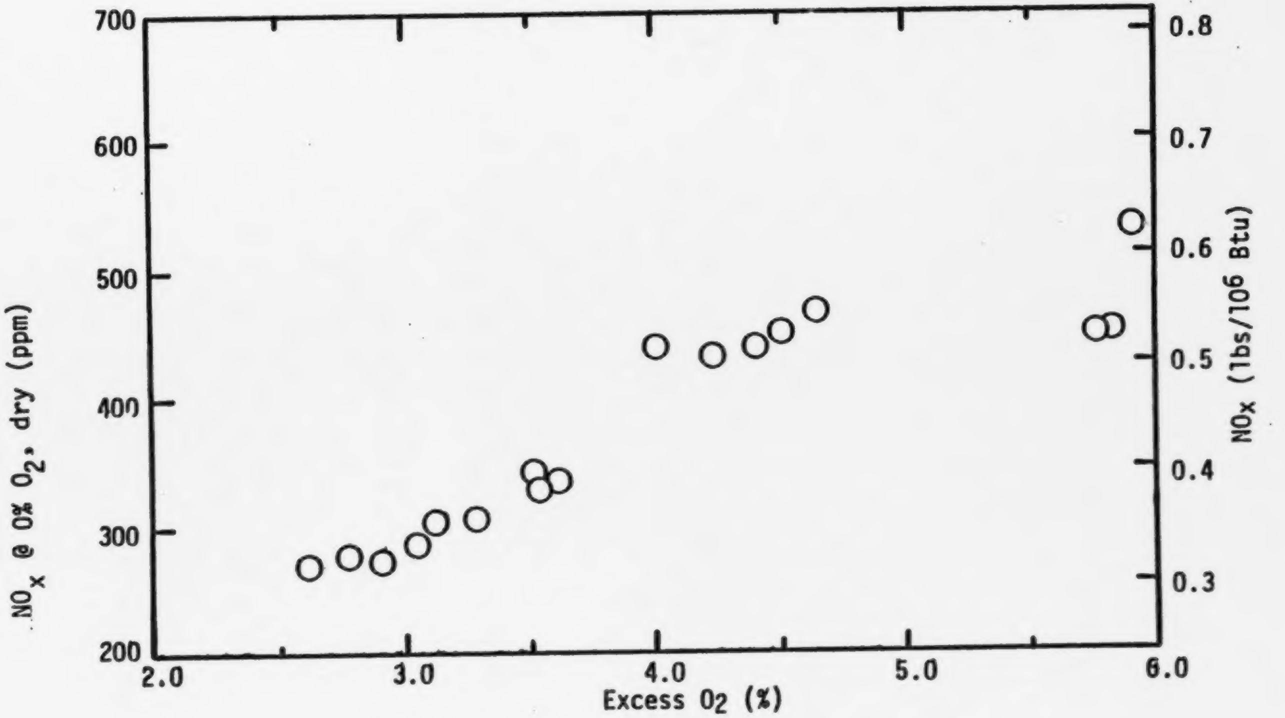
On several previous tests of coal-fired boilers, NO_x emissions have been found to vary linearly with boiler load and excess air levels. Therefore, the hourly NO_x averages were correlated with excess air and load to allow the inclusion of the effects of these variables in the analysis of the NO_x results. Hourly data during load changes were excluded from the analysis. Figures 4-28 and 4-29 show NO_x as a function of excess air at constant loads of 20 MW (full-load) and 14 MW (low-load). At both loads, NO_x increased with excess air at a similar rate. The full-load results show considerable variations at constant excess air levels. In particular, the NO_x levels from 6/13/83 are significantly higher. These variations are believed to be due to day-to-day differences in the operation of boiler parameters such as pulverizer performance, and air distribution to the burners. Figure 4-28 also shows the NO_x level obtained during the optimization testing at the same burner settings. This data point correlates with the data obtained during the 30-day test, although it is at a lower excess O_2 level.

Figure 4-30 and 4-31 show NO_x as a function of boiler load at excess O_2 levels of 3.6 and 4.0 percent. For typical coal-fired boilers, NO_x increases with increasing load due to increasing combustion intensity and fuel/air mixing rates. The slight decrease in NO_x with increasing load shown in the figures is due to changes in the degree of staged combustion with changing load. As load changes, the total combustion air flow rate varies linearly with load for fixed overall excess air. However, the primary air flow rate remains approximately constant. Thus, the burner zone stoichiometry increases as load is reduced, increasing NO_x emissions.



All Data at Constant Load of 20 Mw ± 0.1 Mw

Figure 4-28. NO_x emissions at 20 MW during initial 30-day test.



All Data at Constant Load of 14 Mw ± 0.1 Mw

Figure 4-29. NO_x emissions at 14 MW during initial 30 day test.

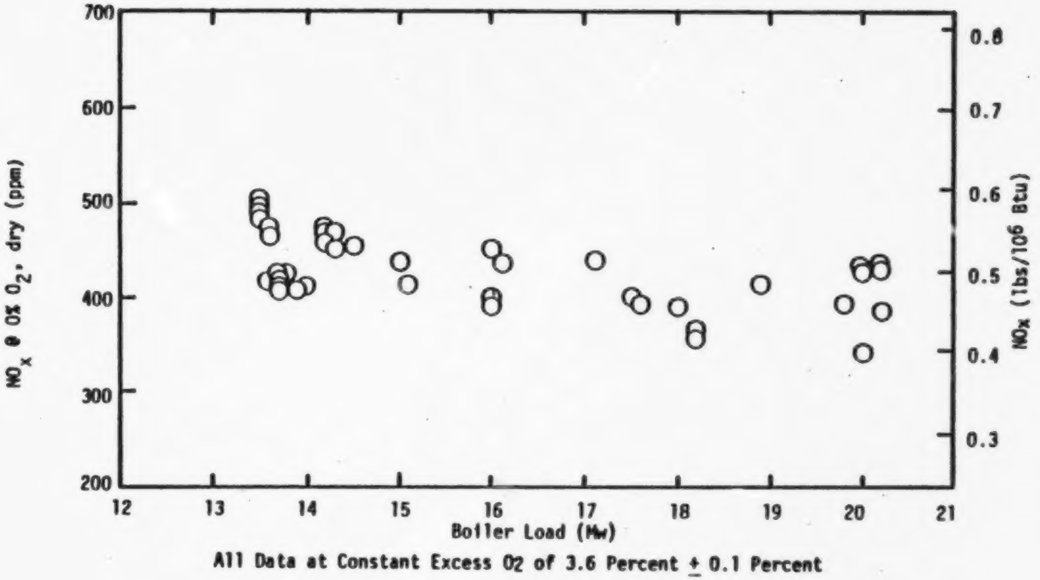
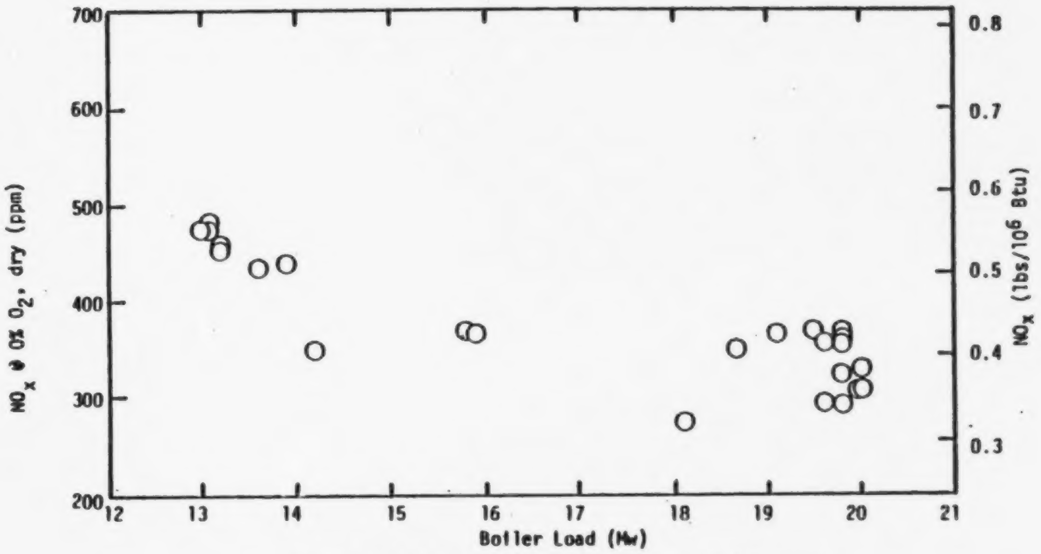


Figure 4-30. NO_x emissions at 3.6 percent O_2 during initial 30-day test.



All Data at Constant Excess O_2 of 4.0 ± 0.1 Percent

Figure 4-31. Effect of load on NO_x emissions during initial 30-day test.

4.6.1.3 Other Emissions

Pollutants evaluated other than NO_x included CO, hydrocarbons, particulate SO_3, HCN and NH_3. These emissions were measured to determine if operation with reduced NO_x levels resulted in increased emissions of other pollutants.

CO emissions are of particular interest because CO provides an indication of combustion efficiency, in addition to being a pollutant. In coal-fired boilers CO typically is constant at normal excess O_2 levels and shows a sharp increase at reduced O_2 levels. CO is generally not directly related to boiler load. Figures 4-32 and 4-33 show CO hourly averages as a function of excess air at low-load and full-load. At low-load the CO remained below 50 ppm at excess O_2 levels above 3.5 percent. At excess O_2 of 2.5 to 3.5 percent, CO showed a gradual increase with decreasing O_2. At full-load, however, CO showed increased emissions at O_2 levels even above 4.0 percent. As with the NO_x results, data from 6/13/83 were significantly different from the majority of the data due to unknown variables in the boiler operation. During the optimization tests, CO of less than 50 ppm was measured at an O_2 level of 3.4 percent. The increased CO during the 30-day test is suspected to be due to a change in the burner balance or a decrease in the coal fineness produced by the coal pulverizers. Figure 4-34 shows CO as a function of load at a constant excess air of 4.0 percent. At this O_2 level, CO was less than 55 ppm below loads of 19.5 MW, but a range of CO emissions was produced at full load. This was due to the change in performance during the test related to burner balance and coal fineness.

Hydrocarbons were monitored for several hours at the beginning and end of the 30-day test period. All concentrations measured were less than 1 ppm as propane. SO_3 concentrations were measured on 6/27/83 and varied from 21 to 88 ppm at 0 percent O_2, with an average of 47 ppm. These results are in the range of typical SO_3 emissions with coal of a similar sulfur content. HCN and NH_3 were measured to determine if any reduced nitrogen compounds were present. HCN and NH_3 concentrations were both less than 1 ppm.

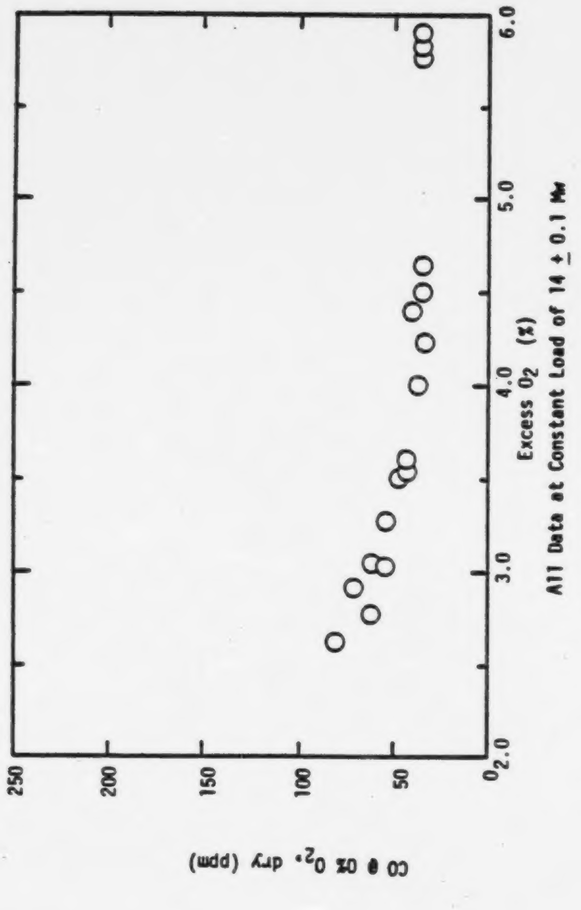


Figure 4-32. CO emissions at 14 MW during initial 30-day test.

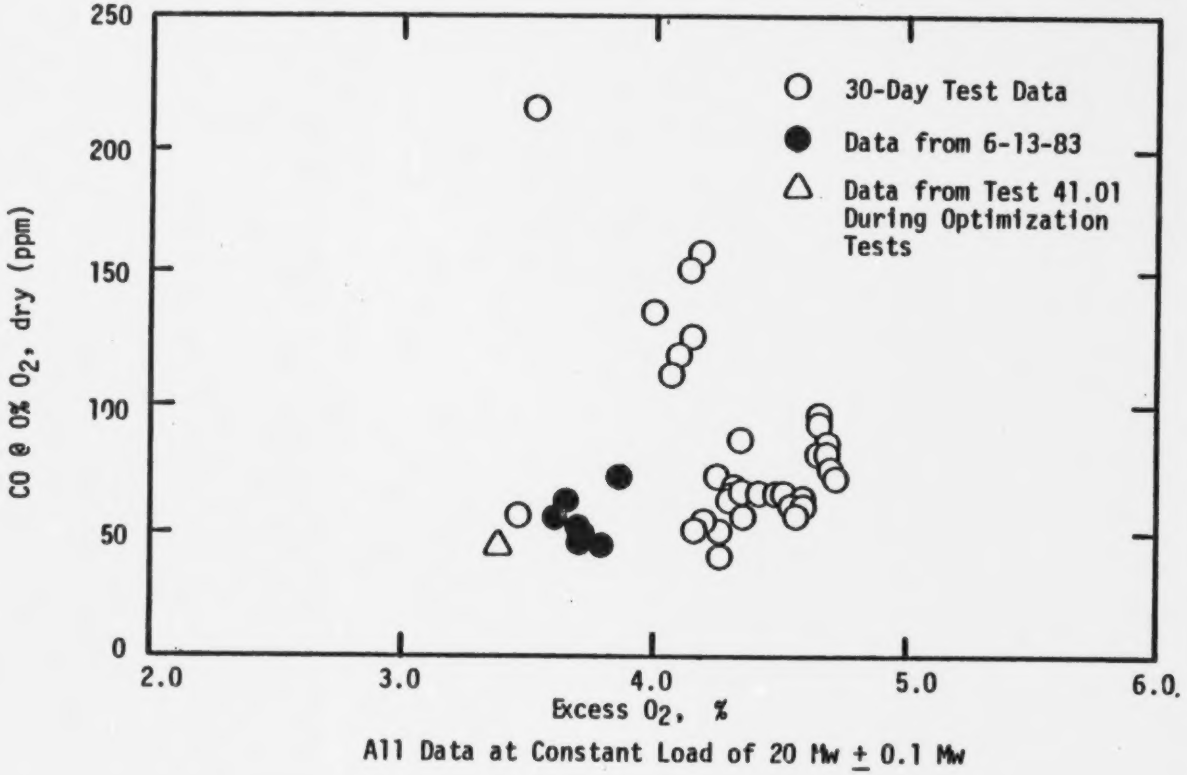
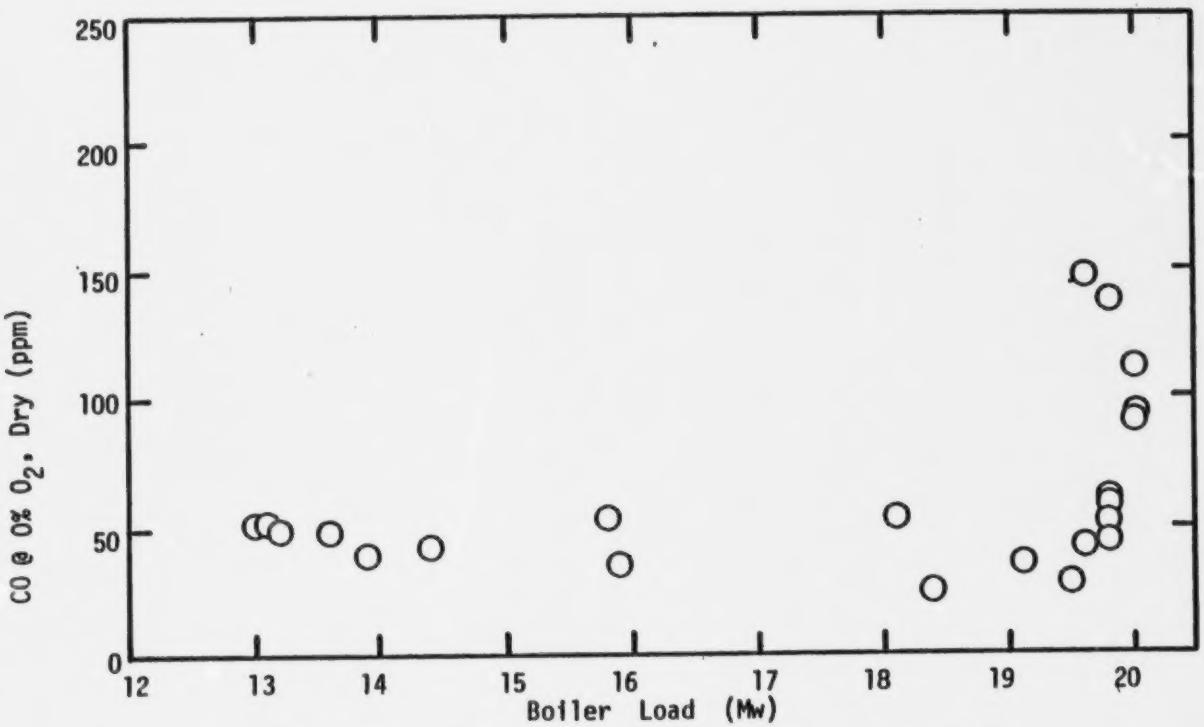


Figure 4-33. CO emissions at 20 MW during initial 30-day test.



All Data at a Constant O_2 of 4.0 Percent ± 0.1 Percent

Figure 4-34. Effect of load on CO emissions during initial 30-day test.

Particulate emissions results are shown in Table 4-11. Three test runs were made on two days near the end of the 30 day test. The results are also expressed as pounds of particulate/pound of ash in coal, so the results can be compared to results with coals of varying ash content. A higher particulate concentration was measured 6/28/83 than on 6/24/83. CO emissions were also higher on 6/28/83 indicating possibly a higher carbon content in the particulate due to lower combustion efficiency. Quality Assurance activities related to the continuous and manual measurements are described in Appendix F.

4.6.1.4 Boiler Performance

Boiler performance was monitored to determine any changes in performance with the DMB. Parameters evaluated included the attainable ranges of load and excess air, operability problems encountered by the plant operators, distribution of combustion air in the boiler and boiler efficiency. Coal characteristics were also monitored to determine the effects of any changes in fuel on performance.

The boiler load ranged from 10 to 20.7 MW during the 30-day test. Burner performance did not cause any limitations in the load range. Excess air ranged from 2.4 to 5.9 percent O_2. The minimum excess air was limited by flame stability and a decrease in combustion efficiency as indicated by an increase in CO emissions. At full load the minimum excess O_2 attained without a CO increase was 4.0 percent. This relatively high excess O_2 level was required due to an imbalance in air distribution to the burners or poor pulverizer performance. The general operability of the boiler reported by the operators was satisfactory during the 30-day test. Slightly increased eyebrows of slag were noted above the burners, but no problems were encountered in operating the burners.

Air distribution was evaluated in terms of combustion staging, burner-to-burner air balance, and oxygen concentrations along the lower portions of the boiler walls. The degree of combustion staging was calculated from measurements of air flows through the various passages. Table 4-12 compares

TABLE 4-11. SUMMARY OF PARTICULATE RESULTS DURING INITIAL 30-DAY TEST

Date	Run No.	Particulate Emissions			
		Grains/SCF @ 0% O_2	lbs/hr	lbs/10^6 Btu	lbs/lbs Ash in Coal
6-24-83	1	5.43	2045	7.63	0.670
6-28-83	2	5.92	2132	8.33	0.731
6-28-83	3	6.49	2370	9.12	0.800
	Avg.	5.95	2182	8.36	0.734

TABLE 4-12. COMPARISON OF BURNER ZONE AND TOTAL STOICHIOMETRY DURING THE OPTIMIZATION TESTS AND INITIAL 30-DAY TEST

Test Series	Total Stoichiometry SR_T	Burner Zone Stoichiometry, SR_B
Optimization (41.01)	119%	78%
30-Day (6-22-83)	124%	80%

TABLE 4-13. STRATIFICATION IN EXHAUST DUCT DURING INITIAL 30-DAY TEST

	Probe No. (North to South)			
	1	2	3	4
Test Series	O_2 (%)			
Optimization (41.01)	3.4	3.7	3.4	3.6
30-Day (6-22-83)	3.6	3.9	5.0	5.2
	CO (ppm)			
Optimization (41.01)	44	39	39	39
30-Day (6-22-83)	105	68	24	22

burner staging as indicated by the burner zone stoichiometry and total stoichiometry for Test 41.01 and on 6/22/83. Test 41.01 was selected during the optimization tests as the operating condition of the 30-day test. 6/22/83 was a typical test day in the latter portion of the 30-day test during which the boiler operated at full-load. Comparison of the stoichiometries shows that burner staging did not change significantly during the 30-day test.

The burner-to-burner balance of air was evaluated from measurements of O_2 and CO stratification in the boiler exhaust. The change in these gas concentrations in the exhaust from north to south reflects the balance of air and fuel to the north burners (1 and 3) and the south burners (2 and 4). Stratification results for Test 41.01 and for 6/22/83 are compared in Table 4-13.

These results indicate that the air/fuel distribution was balanced during Test 41.01, but became unbalanced by 6/22/83. The burner imbalance could have been due to a number of factors as was discussed in Section 4.3. The change may have been caused by changing slag build-up around the burners during the 30-day test. The change in air distribution resulted in insufficient excess air on the north side of the boiler and thus required operation at higher excess air levels to avoid incomplete combustion in burners 1 and 3, and a resulting increase in CO emissions. Operation at increased excess air resulted in increased NO_x emissions and decreased boiler efficiency.

Gas concentrations were also measured at sample taps in the walls of the boiler at the level of the lower burners. The objective of these measurements was to determine the presence of an oxidizing or reducing atmosphere along the boiler walls. Results are summarized in Table 4-14. During operation at low excess air midway through the 30-day test, oxygen on the rear and south wall was less than 1 percent but much higher on the north wall. Similar conditions existed on the south wall during the baseline tests with the original burners. Thus the low oxygen concentrations in the lower furnace may be due to a characteristic of the WIPCO boiler rather than the

TABLE 4-14. FURNACE WALL GAS COMPOSITION DURING INITIAL 30-DAY TEST

Date	Location	O_2 (%)	CO (ppm)
6-14-83	Rear Wall	0.35	> 2000
6-14-83	South Wall	0.25	> 2000
6-15-83	North Wall	3.1	115
6-24-83	Rear Wall	1.5	> 2000
6-24-83	South Wall	1.3	> 2000
6-24-83	North Wall	2.8	115

burners. At increased excess air during the efficiency test on 6/22/83, higher oxygen concentrations prevailed on all the furnace walls.

Combustion efficiency expressed as carbon utilization was estimated from the analysis of coal and ash samples. Results from selected test days are shown in Table 4-15. Carbon in the ash is also shown as an approximate indicator of combustion efficiency. Combustion efficiency during the 30-day test was comparable to the efficiency during the optimization test. The results shown are during days of low CO emissions. Increased CO emissions experienced during portions of the 30-day test would be expected to result in combustion efficiencies 1 to 2 percent lower.

Table 4-16 summarizes the analyses of selected coal samples. Considerable variations occurred in the coal composition, as shown in the analyses of nitrogen, sulfur, ash and moisture. The slagging potential of the fuel as represented by the ash fusion temperatures did not vary. Table 4-17 shows the results of coal fineness testing performed early in the optimization testing and during the latter portion of the 30-day test. Coal fineness from both mills was considerably worse during the 30-day tests, indicating a degradation in mill performance or a coal with a harder grindability. These results compare to a design point of 70 percent. The poor fineness would be expected to cause decreased boiler performance in such areas as combustion efficiency, and CO and particulate emissions.

4.6.1.5 Comparison to Baseline

Table 4-18 compares average boiler operating conditions and emissions during the initial 30-day test of the DMB with the results of the three baseline test series with the original burners. NO_x emissions with the DMB were reduced nearly 50 percent compared to the original burners. CO emissions for the DMB during the 30-day test were increased over the baseline values probably due to burner imbalance and reduced coal fineness. Other emissions with the DMB and original burners were comparable. SO_3 emissions appear higher with the DMB. However, this increase is not considered significant due to the high variability of this measurement.

TABLE 4-15. CARBON UTILIZATION DURING INITIAL 30-DAY TEST

TEST SERIES	DATE	CARBON UTILIZATION (%)	CARBON IN ASH (%)
Optimization (Test 41.01)	5/19/83	98.71	7.06
30-Day	6/13/83	98.96	6.53
30-Day	6/24/83	98.62	6.28

TABLE 4-16. SUMMARY OF COAL ANALYSES DURING INITIAL 30-DAY TEST

Test Series	Optimization		30-Day			
Date	5-18-83	5-18-83	5-25-83	5-29-83	6-20-83	6-24-83
Carbon (Wt. %, dry)	65.18	63.27	64.49	66.97	65.83	67.30
Hydrogen (Wt. %, dry)	4.65	4.49	4.39	4.66	4.61	4.72
Nitrogen (Wt. %, dry)	1.28	1.19	1.29	1.34	1.31	1.15
Sulfur (Wt. %, dry)	3.98	6.09	5.31	4.29	3.52	4.31
Ash (Wt. %, dry)	11.36	13.70	14.31	11.99	12.72	13.74
Moisture (Wt. %)	---	---	14.83	11.96	9.51	9.02
Heating Value (Btu/lb, dry)	---	---	---	---	---	12058
Ash Fusion Temperatures (°F)						
Oxidizing Atmosphere						
Initial Deformation				2360		2380
Softening				2500		2500
Hemispherical				2520		2540
Fluid				2560		2560
Reducing Atmosphere						
Initial Deformation				1920		1930
Softening				2020		1970
Hemispherical				2070		1980
Fluid				2260		2230

TABLE 4-17. COAL FINENESS DURING INITIAL 30-DAY TEST

Date	Wt. % Through 200 Mesh			
	Mill A		Mill B	
	Burner 1	Burner 2	Burner 3	Burner 4
3-16-83	72.4	68.6	69.0	71.0
6-24-83	62.0	59.6	61.0	59.6

TABLE 4-18. NOMINAL BOILER OPERATING CONDITIONS AND EMISSIONS

	TEST SERIES AND DATES			
	Baseline			DMB
	Burner Modification Tests (6/30/80 to 7/12/80)	30-Day Baseline Test Average (7/15/80 to 8/17/80)	Effluent Stream Analysis (3/22/81 to 3/27/81)	30-Day DMB Test Average (5/25/83 to 6/29/83)
Boiler Operating Conditions:				
Load (MW)	20.3	18.5	19.7	16.6
Excess O_2	3.4	3.6	4.0	4.0
Carbon Utilization (%)	99.45	99.36	99.67	98.76
Carbon in Ash (%)	2.69	3.85	1.44	6.62
Emissions:				
NO_x @ 0% O_2 (ppm)	826	847	807	432
CO @ 0% O_2 (ppm)	41	37	32	85
SO_2 @ 0% O_2 (ppm)	3364	3299	4289	3682
SO_3 @ 0% O_2 (ppm)	22	25	35	47
CO_2 @ 0% O_2 (%)	18.9	18.5	18.1	18.3
O_2 (%)	3.4	3.6	4.0	4.0
Hydrocarbons (ppm as C_3)	1	1	4	<1
Total Particulate (gr/scf @ 0% O_2)	7.98	5.93	9.83	5.95
lb particulate/lb ash in coal	0.965	0.828	0.812	0.734
HCN @ 0% O_2 (ppm)	Not Measured	Not Measured	1	<1
NH_3 @ 0% O_2 (ppm)				

The DMB was capable of operating over the same load range as the original burners and did not limit boiler operation due to any deficiencies in burner performance. The minimum excess air levels required with the DMB of 4.0 percent was significantly higher than the excess air levels required with the original burners of 2.5 percent. Operation of the DMB with balanced air distribution, however, would reduce the minimum excess air required.

4.6.2 Second 30 Day Test Period

Results from the initial 30 day tests showed that NO_x emissions were significantly reduced with the DMB compared to the original equipment, pre-NSPS burners. However, combustion efficiency was decreased as reflected in increased CO levels, higher fly ash carbon content, and the resulting lower carbon utilization. The decreased combustion efficiency required operation at higher overall stoichiometry, indicated by excess O_2, resulting in decreased boiler efficiency as well as increased NO_x emissions. Two problem areas, coal fineness and air distribution, were addressed in an additional optimization test series. EER requested that WIPCO adjust mill spring tension to improve coal fineness which was accomplished prior to the start of testing. The objective of the optimization tests was to balance the air distribution to the burners, primarily by using the secondary air sleeves. Balancing the burners would allow operation at lower burner zone stoichiometry and excess air while maintaining low CO emissions and, result in lower NO_x emissions.

An operating condition was found during the optimization tests which produced low CO emissions down to about 2.5 percent excess O_2 with NO_x emission comparable to those measured during the initial 30 day test period. The optimum settings selected for a second thirty day test for two mill, four burner operation were from test 50.01 conducted on August 25, 1983. Test condition 50.01 produced NO_x emissions of 383 ppm, or 0.45 lb/10^6 Btu, with 46 ppm CO at 20 percent express air and an overall burner zone stoichiometry of 76 percent. The burner settings were tested down to 16 MW to verify low load operation with all four burners in operation. Measurements across the backpass indicated balanced O_2, verifying a uniform air flow through the burners and tertiary air ports. The burner settings are listed in Table 4-19 for nominal full load operation. Settings specified for single mill operation were the same as those used during the initial thirty day test, listed in Table 4-19.

The history of emissions and boiler load for this test period is summarized in Figure 4-35. Continuous operation at the optimized settings commenced on August 27, 1983. However, ash deposits formed on the front wall of the boiler and the extended tests of the chosen burner settings were suspended after twelve days on September 7, 1983. The two most probable causes of the day buildup were the resulting flow patterns from the burner settings and coal composition. Plant personnel suspected that the flame shape produced by the burner settings, that is with the ignition point rooted within the burner exit, was the primary cause. Thus, the remainder of the second thirty day test period consisted of adjustments to the burner settings by EER to narrow the flames and move the ignition points into the furnace. Coal samples were obtained for evaluation of slagging tendencies.

4.6.2.1 Emissions During Staged Operation

The overall averages of gaseous emissions for the two phases of the second thirty day test period are summarized in Table 4-20. The average NO_x emissions for the first twelve days, when the burners were operated at constant settings, were 402 ppm or 0.47 $lb/10^6$ Btu. This is about 4 percent higher than was measured for the test condition, 50.01, upon which the burner settings were based. Excess air, indicated by measured O_2 in the flue gas, was closely regulated by the plant operators at about 3.6 percent as specified by EER. Average CO emissions were slightly higher during the first part of the thirty day period than for the optimized test condition. Concentrations of CO_2 and SO_2 did not vary significantly during the first twelve days, indicating consistent coal composition for this period.

In response to the concerns of plant management on the build-up of slag deposits on the front wall of the boiler, operation at the optimized burner settings were suspended. Adjustments to the burner settings were made on a

TABLE 4-19. SECOND 30-DAY TEST BURNER SETTINGS FOR TWO-MILL, FOUR-BURNER OPERATION

BURNER VARIABLE	BURNER SETTING			
	Burner No.			
	1	2	3	4
Nozzle Position, In. from baseline	0	0	0	0
Core Air Valve, °Open	45	45	45	45
Inner Register, °Open	10	10	10	10
Outer Register, °Open	20	10	20	15
Inner Sleeves, % Open	50	50	50	50
Outer Sleeves, % Open	50	50	50	50

NO_x Ports	1A	2A	3A	4A	Outer	Bottom	Center
% Open	100	100	100	100	100	100	100

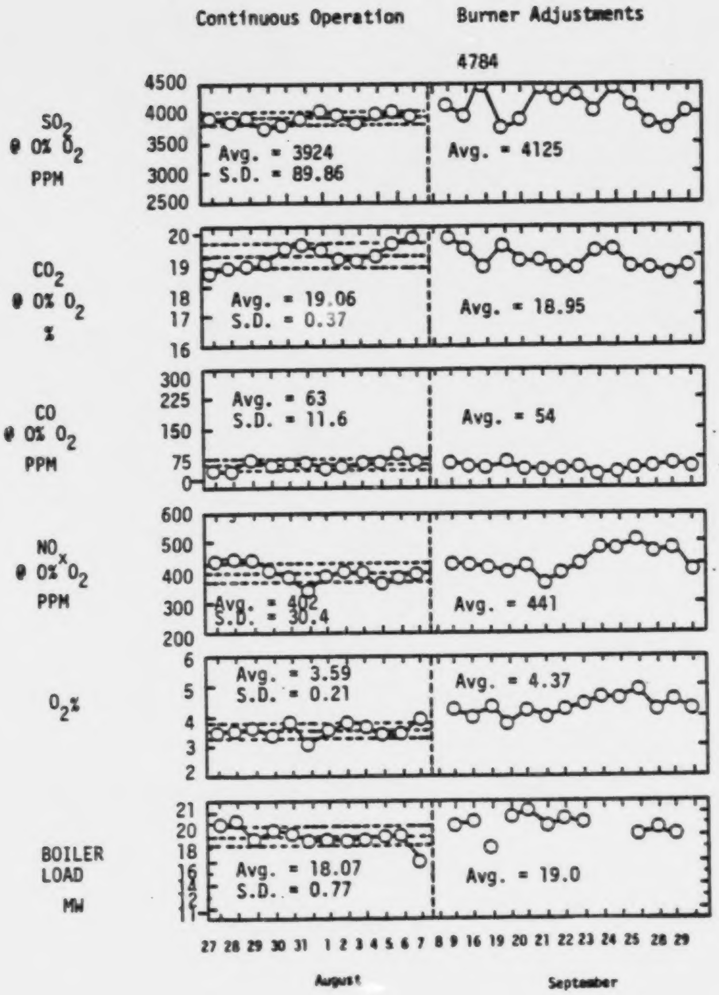


Figure 4-35. Daily averages of emissions during second 30-day test period.

TABLE 4-20. OVERALL AVERAGE OF GASEOUS EMISSIONS FOR CONTINOUS STAGED OPERATION DURING SECOND 30-DAY TEST PERIOD

SPECIES	Aug. 27 - Sept. 7, 1983		Sept. 8 - Sept. 28, 1983	
	Measured	@ 0% O_2	Measured	@ 0% O_2
O_2 (%)	3.59	0	4.37	0
NO_x(ppm)	3 33	4 02	3 49	4 41
CO (ppm)	52	63	43	54
CO_2(%)	15.80	19.06	15.01	18.95
SO_2(ppm)	3253	3924	3267	4125

daily basis for the remainder of the test period. The series of adjustments included pushing in the coal nozzles thereby increasing primary velocity, opening the secondary air registers, adjusting the secondary air sleeves, and varying the core air valve position. Thus, the data shown in Figure 4-35 and Table 4-20 for the period from September 8 to September 28, 1983 represent staged operation at a number of different burner settings. The higher overall NO_x (441 ppm or 0.51 $lb/10^6$ Btu) for the period reflect the effect of decreasing staging by opening the resistors and thus allowing more air through the burner throats. More conservative operation by the plant in an attempt to compensate for the build-up of deposits increased overall excess air to a measured O_2 concentration 4.37 percent. Average CO emissions were slight lower, by about 10 ppm, for the latter part of the test period. The concentration of SO_2 measured varied over a wider range after September 8, 1983, indicating changes in coal compositions.

Hourly averages of NO_x and CO were correlated with excess air and load for the first twelve days of this thirty day test period while constant burner settings were maintained. The effect of excess air, as indicated by measured O_2, on emissions is shown in Figure 4-36 for a load of 20 ± 0.1 MW. Included are the data from test condition 50.01 for comparison, although the load during that test was slightly lower, 18.9 MW. NO_x emissions increased with excess air with most of the data within a range of about 50 ppm. Some of the data from August 28, 29, and 30, however, are higher than the bulk of the data for similar excess air levels. The level of CO emissions, an indication of combustion efficiency, was less than 70 ppm for most test conditions, gradually increasing with decreasing excess air. Differences in emissions are probably associated with daily or shift variations in boiler operation, including pulverizer performances, soot blowing cycle, and burner air distribution. The data obtained during the long term test period are generally consistent with the optimum test conditions. The effect of load on NO_x and CO emissions is shown in Figures 4-37 and 4-38, respectively. The data shown are hourly averages at a constant excess air level, 4.0 ± 0.1 percent O_2. The effect of load is relatively small, with NO_x decreasing from 420 to 380 ppm as load is decreased from 20 to 15 MW. Similarly, CO levels

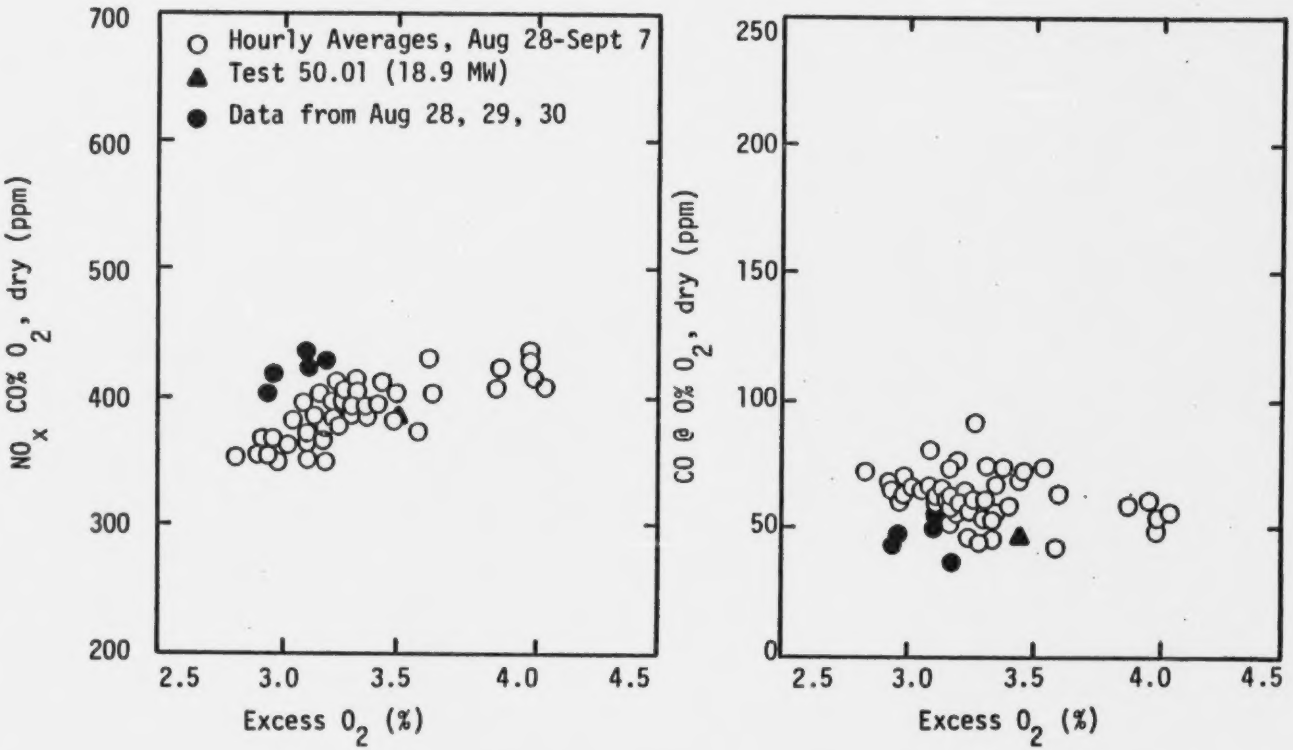
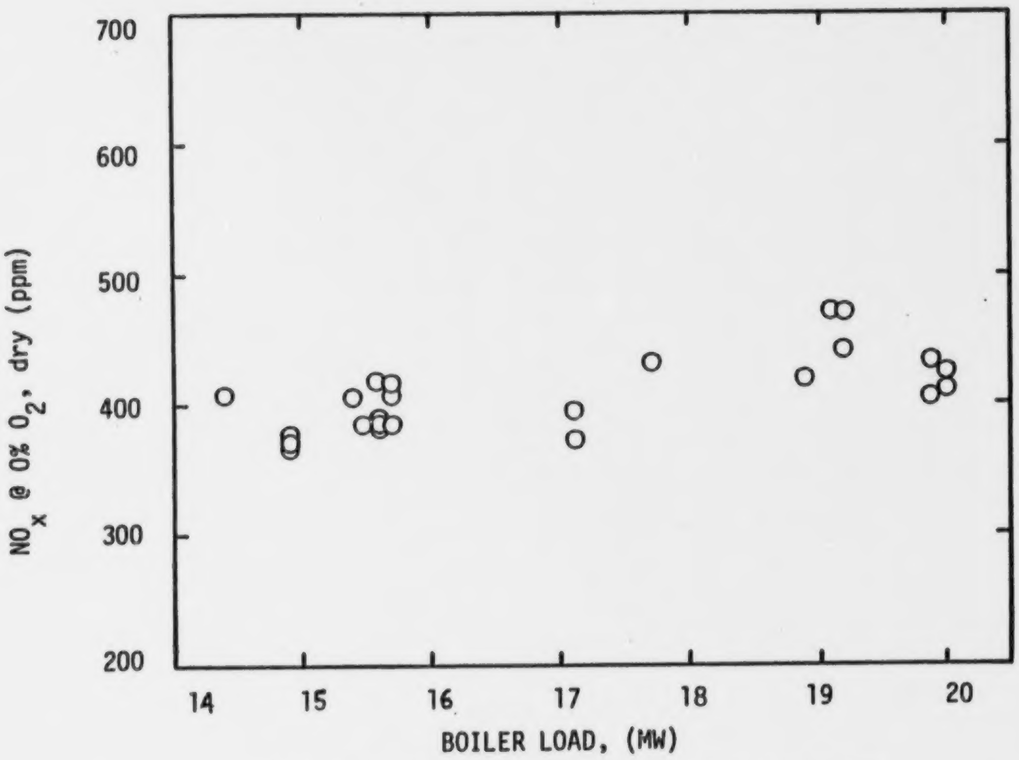
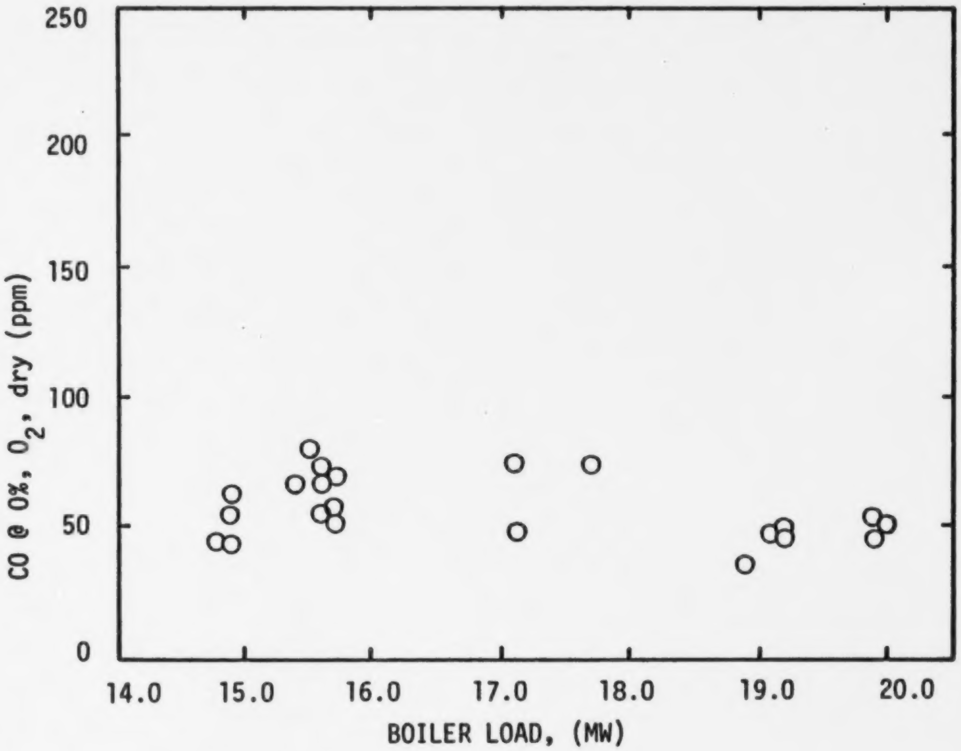


Figure 4-36. Effect of excess air on emissions during first twelve days of second 30 day test period at constant load (20 ± 0.1 MW).



All data at constant O_2 of 4.0 ± 0.1 percent

Figure 4-37. Effect of load on NO_x emissions during first twelve days of second 30 day test period.



All data at constant O_2 of 4.0 ± 0.1 percent

Figure 4-38. Effect of load on CO emissions during first twelve days of second 30-day test period.

increased only slightly at lower loads. Note that these trends are the opposite of those observed during the first 30-day test period.

4.6.2.2 Boiler Operation

The boiler was operated staged (with the tertiary air ports open) from August 27 to September 28, 1983 based on system load demand. For all but three days, the plant had both mills in operation. The typical daily load cycle during this second extended test period had reduced loads (14-16 MW) from 11:00 p.m. until 9:00 a.m. and full load (19-20 MW) from 9:00 a.m. until 11:00 p.m. No problems with flame stability were encountered over this load range.

Ash samples from the multiclone hopper and bottom ash was were analyzed to estimate combustion efficiency. Combustion efficiency expressed as carbon utilization was estimated from analysis of coal and ash samples from typical test days. Results from two days at constant conditions and one day during the burner adjustment tests after September 8, 1983 are summarized in Table 4-21. For the two days during which the boiler was operated at the optimized settings, the carbon content of the ash collected in the multiclone was less than two percent, which comparable to the original equipment Intervane burners and is indicative of high combustion efficiency. Carbon utilization for those two days was well over 99 percent. The ash sample from September 22, 1983 was substantially higher in carbon content, 7.2 percent, and consequently representative of lower combustion efficiency, only 98.09 percent carbon utilization. However, this test is similar to the initial thirty day test period during which selected test days yielded carbon utilization between 98.62 and 98.96 percent.

The most significant impact on boiler operation during this second thirty day test period was the accumulation of ash deposits on the front wall of the boiler. These deposit occurred during the initial twelve days while the burners were operated at constant conditions. At the constant conditions listed previously in Table 4-19, the base of the flames were within the burner exits from which they flared out. The plant operators suspected that

TABLE 4-21. CARBON UTILIZATION DURING SECOND 30-DAY TEST PERIOD

DATE	CARBON IN ASH (Wt %)	CARBON UTILIZATION (%)
8-29-83	1.97	99.50
9-3-83	1.86	99.77
9-22-83	7.20	98.09

this flame shape contributed to the ash deposition on the front wall. Another possible cause that was evaluated was the coal composition. Selected coal samples were analyzed for comparison with the coal fired during the initial thirty day test when there was no deposition problem. Summary of ultimate analyses of coal samples from the second thirty day test period are listed in Table 4-22. These coals are similar in composition to the samples from the first test period listed in Table 4-16 and show considerable variability and exceptionally high sulfur content, an indication of high slagging potential. The characteristic ash fusion temperatures for coals from the initial and second extended test period are compared in Table 4-23. There is essentially no difference in the ash fusion temperatures of the coals from the two test periods.

4.6.2.3 Comparison to Initial 30-Day Test

The burner settings utilized for the second thirty day tests produced mixed results. Emissions, combustion efficiency, and stability were improved over the initial thirty day tests. Average NO_x emissions for the first twelve days at constant burner setting were 402 ppm compared to 432 ppm for the initial thirty day test, even though the average load was about 9 percent higher for the second test period. Combustion efficiency indicated both by CO emissions and fly ash carbon was improved by the second thirty day burner settings, although the test condition was maintained for only twelve days. Average CO emissions were 63 ppm compared to 85 ppm for the initial test period, while carbon utilization was 99.64 percent for the second test period versus 98.76 percent for the first. The CO emissions from the burner settings were also less sensitive to excess air level, with no significant increase down to about 2.5 percent O_2, similar to the baseline burners. However, the burner settings used for the second thirty day test apparently contributed to the accumulation of slag on the front wall of the boiler as a result of the shape of the flames. This accumulation of slag forced the termination of the extended test at the optimized burner settings after twelve days.

TABLE 4-22. SUMMARY OF COAL COMPOSITION DURING SECOND 30-DAY TEST PERIOD.

DATE	8-29-83	9-3-83	9-22-83
Moisture (wt. %)	8.58	9.07	7.19
Carbon (wt. %, dry)	61.92	68.41	61.06
Hydrogen (wt. %, dry)	4.28	4.84	4.51
Nitrogen (wt %, dry)	1.48	1.46	1.24
Sulfur (wt %, dry)	5.46	4.29	4.90
Ash (wt %, dry)	15.32	8.19	14.98

TABLE 4-23. COMPARISON OF ASH FUSION TEMPERATURES OF COAL SAMPLES FROM THE INITIAL AND SECOND 30-DAY TEST PERIODS

TEST PERIOD	INITIAL		SECOND	
SAMPLE DATE	5-29-83	6-24-83	8-29-83	9-22-84
Oxidizing (°F)				
Initial	2360	2380	2360	2420
Softening	2500	2500	2550	2480
Hemispherical	2520	2540	2560	2520
Fluid	2560	2560	2580	2560
Reducing (°F)				
Initial	1920	1930	1930	2020
Softening	2020	1970	1970	2060
Hemispherical	2070	1980	1980	2100
Fluid	2260	2230	2220	2260

4.6.3 Extended Staged Tests of December 1983

During the period December 2-7, 1983, tests were conducted to identify optimum operating conditions. Specific objectives of these tests were twofold:

- Achieve the lowest possible NO_x emissions with a goal of 0.3 lb/10^6 Btu.
- Identify a burner operating point with the lowest possible NO_x emissions commensurate with normal boiler operation.

Following these tests, the emissions were monitored continuously as the operators followed the normal load cycle from December 8 to December 22, 1983.

4.6.3.1 Optimization Tests

The optimization tests were conducted at a nominal load of 20 MW and involved adjusting the burner settings to obtain the lowest burner zone stoichiometry and NO_x emissions commensurate with acceptable flame stability and efficiency. Minimum NO_x emissions of about 0.35 lb/10^6 Btu were achieved. However, it was not possible to identify an operating point acceptable for unattended operation at this low emission level. Three recurring problems were experienced and had to be addressed:

- Acceptable flame shape for long term operation.
- Hazy lower furnace gases.
- Bistable burner operation.

The results of previous tests, particularly the second thirty day test period, suggest that flames rooted within the burner exit may contribute to front wall slagging. These optimization tests showed that the stand off distance of the flame was sensitive to burner settings. At one low NO_x operating condition, for example, changing the outer register position for one burner from 30 degrees open to 35 degrees open caused the flame to lift off the burner exit over 3 ft. Such large stand-off distances increase premixing at the base of the flame, defeat the desired DMB flow patterns and increase NO_x emissions. Also the flame scanner signals become marginal. This change occurred at a relatively high windbox-to-furnace pressure differential of about 2.5 inches H_2O. Opening the register at this fairly high pressure differential increased the burner zone stoichiometry and overall stoichiometry in the furnace adjacent to that burner and decreased in the degree of swirl. Changes in excess air, load, fuel composition, or pulverizer operation could cause similar changes. This sensitivity was also observed for the original equipment burners during baseline boiler characterization tests as well as for the DMBs with and without the tertiary air ports open. Thus, to maintain optimum flame shapes, periodic burner adjustments were required. It should be noted that this sensitivity is considered "normal operation" by the WIPCO operators. Typically the operators adjust the registers at least once per shift. The operators prefer flames with the greatest stand-off distance commensurate with a strong scanner signal. Under this condition, slight changes in burner settings can significantly impact flame shape.

Under some low NO_x operating conditions, the furnace gases were hazy. Under normal operating conditions when the bottom-ash is discharged, light (flame radiation) can be seen in the bottom-ash hopper view port. The operators utilize this light as an indication that the hopper throat has not been obstructed with ash. However, the hazy furnace gases observed with some low NO_x operating conditions apparently absorb the radiant light from the flames. Then, no light can be seen in the ash hopper. The operators consider this type of operation to be unacceptable. The hazy furnace gases are probably caused by soot formation in the flames from some burners operated at abnormally low burner zone stoichiometry due to imbalance. Operation of all burners at a burner zone stoichiometry near design point, about 70 percent theoretical air, with a uniform distribution of air throughout the windbox would alleviate this problem.

Fixed burner-settings had resulted in considerable variation in performance in previous tests. This bistable operation had been a major hindrance in the testing at WIPCO. During initial optimization tests, the burners were returned to a baseline operating condition with the tertiary air ports closed at the completion of each day of testing. In many cases on subsequent days of testing, the performance was found to be considerably different at the same burner settings with the tertiary air ports open. Also, midway through the first thirty day test at fixed burner settings, the stratification in the exhaust duct changed indicating a change in burner performance. This change in air distribution required an increase in overall excess air level to compensate for the low air flow to one side of the boiler and thus maintain low CO emissions. However, this increased air flow increased NO_x emissions.

These problems hampered the optimization tests in December 1983 as well. As a result, it was not possible to define specific burner settings which would maintain low NO_x conditions at WIPCO for an extended period. Consequently, following a series of burner adjustment tests, the plant operators were requested to operate the unit at settings which produced balanced performance with NO_x emissions of about 0.45 lb/10^6 Btu. The operators were instructed to maintain the settings specified by EER unless flame shape, stability, or other problems required changes. The initial settings for the extended test period are listed in Table 4-24.

4.6.3.2 Continuous Emissions Monitoring

The daily averages of emissions and boiler load during the extended tests of December are shown in Figure 4-39. During this period the plant operators experienced difficulty in maintaining stable flame scanners signals and in operating the unit on automatic control. Thus, a considerable number of adjustments were made to the burner settings although the tertiary air ports were left open. Adjustments were made to outer register position, inner secondary sleeve position, and core air valve position. Also, the operators maintained higher excess air levels (over 4 percent) than specified by EER (about 3.5 percent). The average burner zone stoichiometry for this

TABLE 4-24. INITIAL BURNER SETTINGS FOR DECEMBER 1983 EXTENDED STAGED TESTS - TWO MILL, FOUR BURNER OPERATION

BURNER VARIABLE	BURNER 1	2	3	4
Nozzle Position (in from baseline)	0	0	+1	+1
Core Air Valve (° Open)	70	70	75	60
Inner Register (° Open)	10	10	10	10
Outer Register (° Open)	33	34	30	30
Inner Sleeves (% Open)	25	25	100	100
Outer Sleeves (% Open)	100	100	100	100
NO_x Ports - - - All tertiary air ports 100% open				

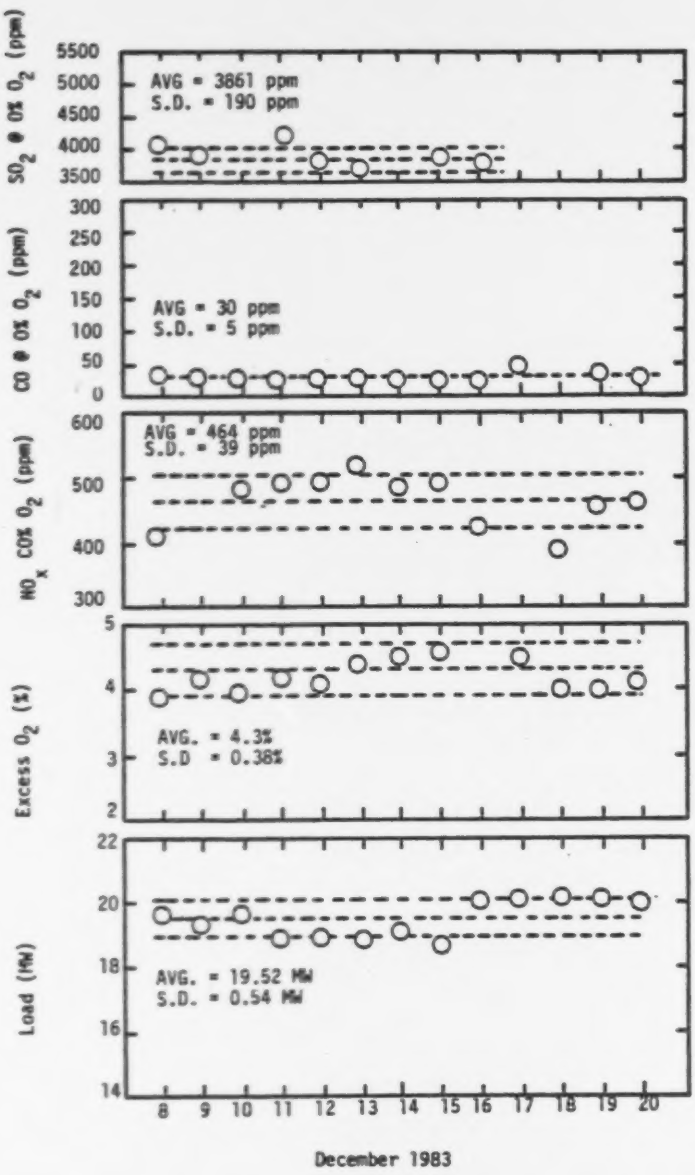


Figure 4-39. Daily averages of staged operation during December 1983.

test period was about 85 percent for the excess O_2 level of 4.3 percent. At these conditions, this NO_x emissions for the 13-day period averaged 464 ppm or 0.54 lb/10^6 Btu. CO emissions averaged a low 30 ppm.

Combustion efficiency was evaluated for selected conditions representing the beginning, middle and end of this test period. Ash samples obtained from the dust collector hopper were evaluated for carbon content and/or weight loss on ignition at 750°C. Loss-on-ignition is directly related to unburned combustibles of the sample, principally carbon for coal combustion. The results of the ash analyses are listed in Table 4-25. The wide range of carbon burnout, from 1.88 to 8.20 percent loss on ignition, is indicative of the different burner settings utilized during the test period.

4.6.4 Final Extended Test Period

The testing of the DMB concept at WIPCO was completed with a final extended test period from January 13 to March 26, 1984. The objectives of this test period were two-fold. First, low emissions were to be demonstrated while the boiler was operated by plant personnel according to system demand. Adjustments were to be made as necessary to balance burner performance and maintain flame characteristics acceptable to the operators. Second, for approximately the last month the lowest possible NO_x emissions were to be maintained with burner adjustments by EER personnel made on a daily basis. The previous extended test periods had shown that burner performance at WIPCO can change over time for constant settings. Low emissions were expected to be maintained by adjustments to the burner settings to compensate for any observed bistable operation.

Prior to the start of extended staged operation, burner adjustments were made to identify settings to be maintained during the first month of this test period. These settings are summarized in Table 4-26. Again, for single mill operation the settings listed in Table 4-9 were used. These initial burner settings, with minor adjustments, were used until February 24, 1984 when the second of this test period began with daily burner adjustments.

TABLE 4-25. ANALYSIS OF FLY ASH SAMPLES FROM DECEMBER 1983 TEST PERIOD

SAMPLE DATE	LOSS ON IGNITION @ 750°C (Wt. %)	CARBON CONTENT (Wt. %)
12-9-83	6.91	-----
12-15-83	8.20	-----
12-20-83	1.88	2.05

TABLE 4-26. INITIAL BURNER SETTINGS FOR FINAL EXTENDED TEST PERIOD FOR TWO-MILL, FOUR BURNER OPERATION

	BURNER SETTING			
	BURNER NO.			
BURNER VARIABLE	1	2	3	4
Nozzle Position, in from baseline	0	0	+1	+1
Core Air Valve, ° Open	55	55	60	60
Inner Register, ° Open	10	10	10	10
Outer Register, ° Open	32	33	27	31
Inner Sleeve, % Open	75	45	80	45
Outer Sleeve, % Open	65	60	80	80
NO_x Ports, % Open	All NO_x Ports 100% Open			

The history of emissions and boiler load for this test period is summarized in Figure 4-40. Continuous monitoring of emissions with the burners at the initial settings began January 20, 1984. By about January 31, ash deposits had developed on the front wall of the boiler in the form of eyebrows built up around the burners. At that time the boiler operators requested opening the secondary air sleeves to increase the flow of air through the burner throats and thus move the bases of the flames further into the furnace to alleviate the deposition problem. Staged operation with the sleeves fully open continued until February 24, 1984 when the second phase of tests started. Attempts to dislodge the eyebrows prior to this second phase of tests were unsuccessful and testing proceeded. The burner adjustments focused on increasing the degree of staging by diverting air to the tertiary air ports while maintaining balanced air distribution. This was accomplished by progressively closely registers and secondary sleeves. This altered the shape of the flames and moved the ignition points back toward the throat. The front wall deposits softened and weakened falling to the bottom of the boiler. Eventually, this resulted in slag bridging across the hopper necessitating a brief outage to remove the deposits from March 3 to March 8, 1984. Problems were encountered with the flame scanner system delaying further staged testing until March 22, 1984. Testing was suspended on March 28 just prior to the scheduled spring outage beginning March 30, 1984.

4.6.4.1 Emissions During Staged Operation

The overall averages of daily gaseous emissions are summarized in Table 4-27 for three distinct periods of this final testing effort. The average NO_x emissions for the first thirty five days, January 13 to February 23, 1984, during which the burners operated at essentially constant settings were 464 ppm, or 0.54 $lb/10^6$ Btu. There were, however, large variations in excess air and load resulting in the wide range of NO_x emissions seen in Figure 4-39. Excess air, indicated by the measured O_2 in the flue gas, was not as closely regulated by the operators during this initial period as in the previous thirty day tests. Daily averages of excess O_2 ranged from 3.1 to 4.8 percent. For the common windbox arrangement at WIPCO, changes in excess air also affect burner zone stoichiometry for constant settings with the

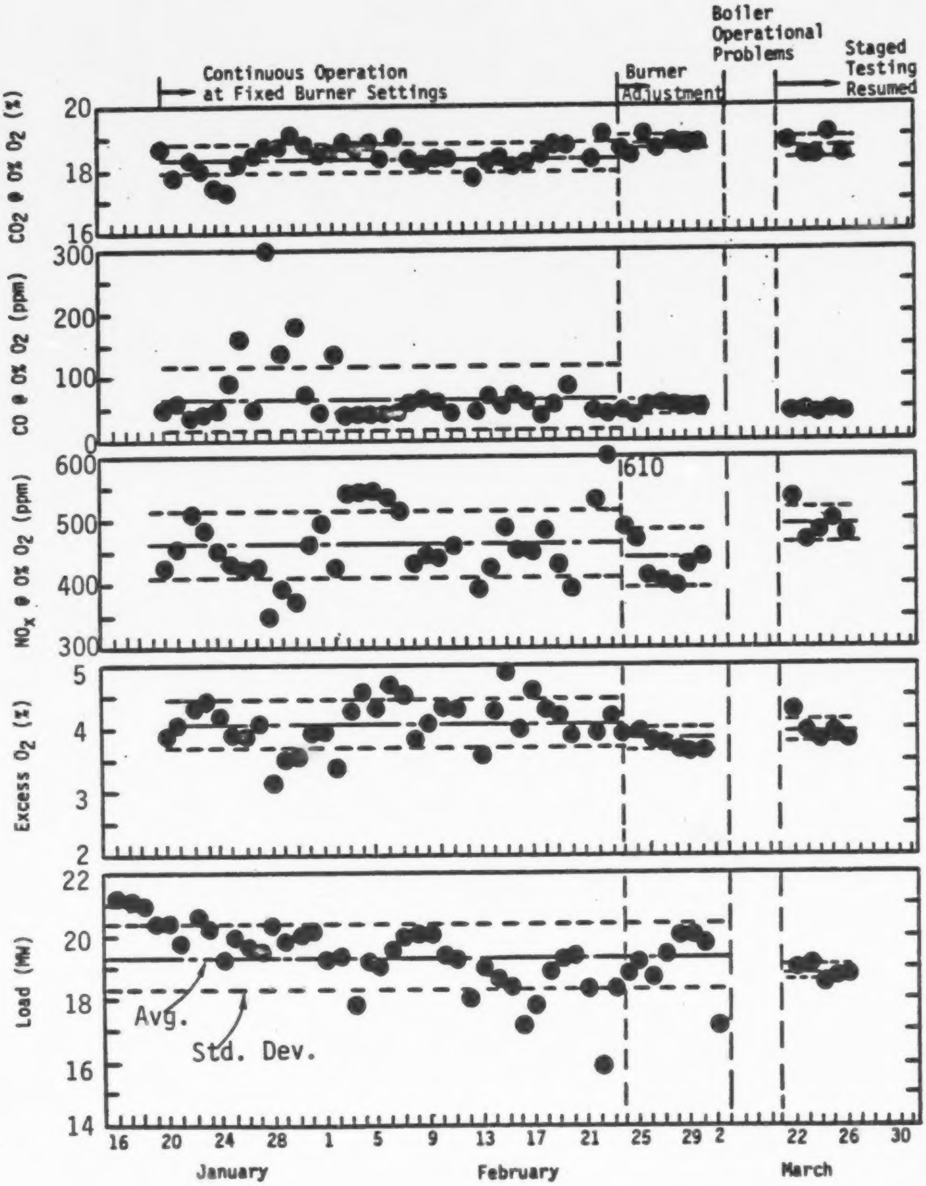


Figure 4-40. Daily averages of staged operation during final test period in 1984.

TABLE 4-27. SUMMARY OF EMISSION DURING FINAL EXTENDED TEST PERIOD

SPECIES	Jan. 13 - Feb. 23, 1984		Feb. 24 - Mar 2, 1984		Mar 22 - Mar 27, 1984	
	Measured	@ 0% O_2	Measured	@ 0% O_2	Measured	@ 0% O_2
O_2	4.05	0.0	3.82	0.0	3.94	0.0
NO_x	375	464	360	440	398	490
CO	52	65	41	50	32	40
CO_2	14.83	18.37	15.32	18.73	15.09	18.57

burner zone stoichiometry ranging from 82 to 86 percent of theoretical stoichiometric air. NO_x emission have been shown to be very sensitive to the degree of staging as well as excess air which explains the wide range of NO_x emissions, 350 to 610 ppm, measured during this period. High CO levels were measured from January 25 to February 2 during days with low O_2 levels. Closer regulation of excess air would have minimized the indicated burnout problems.

For the second period from February 24 to March 2, during which burner adjustments were made to achieve the lowest possible emissions, NO_x averaged 440 ppm or 0.51 lb/10^6 Btu. The operators maintained closer control of the excess air with O_2 between 3.6 and 4.0 percent. CO levels were substantially lower than during the first period, 50 ppm compared to 64 ppm. Lower burner zone stoichiometry was also achieved as a result of the burner adjustments, 75 to 80 percent. The range of burner settings which produced these results is listed in Table 4-28.

After delays resulting from plant operational problems, including a brief outage to remove slag deposits from the furnace and problems with the flame scanner system, testing resumed on March 22 and continued through March 27. NO_x emissions were much higher with an overall average of 490 ppm or 0.57 lb/10^6 Btu. To maintain stable scanner signals it was necessary to retract the coal nozzles for burners 3 and 4. This improved stability by increasing the degree of coal and air mixing, thus resulting in the higher measured NO_x. CO levels were correspondingly lower indicating improved combustion efficiency. Burner zone stoichiometry ranged from 79 to 85 percent for the burner settings listed in Table 4-29. The data indicate that lower excess air levels, less than the average 3.94 percent O_2, could have yielded somewhat lower NO_x emissions, however the operators were more conservative as a result of the problems experienced with the scanner system.

4.6.4.2 Boiler Operation

The WIPCO boiler was operated staged for a total of 45 days from January 13 to March 27, 1984 while meeting system electrical demand. The plant was

TABLE 4-28. RANGE OF BURNER SETTINGS FROM FEBRUARY 24 TO MARCH 2, 1984

VARIABLE	BURNER SETTING			
	BURNER NO.			
	1	2	3	4
Nozzle Position, in from baseline	0	0	0	0
Core Air Valve, ° Open	50-60	60	60	60
Inner Register, ° Open	10	10	10	10
Outer Register, ° Open	15-20	15-20	15-30	15-30
Inner Sleeve, % Open	30-50	30-50	30-50	30-50
Outer Sleeve, % Open	23-30	22-50	30-40	30-50
NO_x Ports, % Open	All Ports 100% Open			

TABLE 4-29. RANGE OF BURNER SETTINGS FROM MARCH 22 TO MARCH 27, 1984

VARIABLE	BURNER SETTING			
	BURNER NO.			
	1	2	3	4
Nozzle Position, in from baseline	0	0	0	0
Core Air Valve, ° Open	90	80	60	60
Inner Register, °Open	10	10	10	10
Outer Register, °Open	15	15	15	15
Inner Sleeve, % Open	30-100	30-100	30-100	30-100
Outer Sleeve, % Open	30-100	30-100	35-100	40-100
NO_x Ports, % Open	All ports 100% Open			

dropped to single mill operation, 10-11 MW, for four to five hours during only four days in that time span. Typical diurnal variations in load had reduced loads (15-17 MW) from midnight to 9:00 a.m. and full load (19-20 MW) from 9:00 a.m. to midnight. No stability problems related to actual burner operation were encountered over this load range.

Combustion efficiency expressed as carbon utilization was estimated from analysis of coal and ash samples from typical test days, summarized in Table 4-30. For the first period at constant burner settings, selected test days yielded estimated carbon utilization of 97.19 to 99.27 percent. Other ash samples in that period, analyzed for unburned combustibles only, ranged from 2.53 to 7.74 percent loss on ignition. The analysis of samples obtained during the later burner adjustment period indicate improved burnout for similar NO_x levels. This improvement is probably due to more balanced air distribution resulting from the daily adjustment and "optimization" of burner settings. Additional daily samples from this period analyzed for unburned combustibles ranged from 3.25 to 5.68 percent loss on ignition.

Two operational problems did occur during this test period. During the initial phase, January 13 to February 23, 1984, there was a significant build up of ash deposits in the form of eyebrows around the lower burners. This build up was probably related to the coal characteristics and possibly the flame characteristics. During these tests, the plant received a coal shipment which WIPCO management suspected to be of low quality. In addition, prior to receiving this suspect shipment, the coal supply was depleted to such an extent that the coal at the bottom of the storage pile was used. The coal at the bottom of the bile was only used to keep the unit running, being of questionable quality. Samples of coal burned on January 20, February 1 and 15 were high sulfur (5.32, 6.53, and 4.92 percent, dry) and high ash (15.21, 15.89, and 14.61 percent, dry) coals.

Attempts to remove the eyebrows and slag around the burners prior to the final test period were unsuccessful. The burner adjustment tests began February 24 with the deposits still present. The burner adjustments included closing the registers to divert air to the tertiary air ports and to produce

TABLE 4-30. CARBON UTILIZATION DURING SECOND 30-DAY TEST PERIOD

DATE	CARBON IN ASH (WT %)	UTILIZATION (%)	CO (ppm)	NO_x (ppm)
1-19-84	5.45	98.67	62	432
1-31-84	8.06	98.09	72	462
2-14-84	8.50	97.19	64	425
2-23-84	2.53	99.27	40	609
2-24-84	4.18	99.15	39	518
2-27-84	7.40	98.56	63	406
3-23-84	5.53	98.60	41	462
3-36-84	3.82	99.35	38	474

high swirl to pull the ignition point of the flames back to the burner exit. This caused the flames to envelope the eyebrows around the burner exits. The slag deposits were apparently weakened by this heating and resulted in large chunks of slag falling to the bottom of the furnace. A few days after these burner adjustments, the light visible in the ash tank was was observed to grow dimmer. Closer inspection revealed that ash and slag had bridged across the throats of the hopper, causing ash to fill the furnace hopper. This forced an outage, from March 2 to 7, to remove the accumulated material.

Following the outage, problems occurred with the ability of the flame safety system to detect stable coal flames. The initial problem was an erratic and weak main flame signal from burner 1 as the unit was brought up to load after the outage. Plant personnel performed standard maintenance and adjustments without success. Forney Engineering was called in to service the scanner so that testing could resume as soon as possible. Forney traced the problem to a faulty main flame scanner amplifier and subsequently checked and adjusted the amplifiers for the other burners. While the Forney representative was still on site, a problem occurred with the detected stability of the burner 4 main flame. The stability problem persisted after verification of scanner system operation by the Forney engineer.

Potential causes of this instability evaluated included:

1. Air distribution to each burner
2. Coal fineness
3. Physical obstructions in and around the burner

Air distribution to each burner was determined using the flow indication devices incorporated into the burner design. No deviations outside the normal range were observed. In addition, check of flue gas stratification did not indicate any abnormal deviations, with less than 1.0 percent O_2 difference between the north to south side. The south side actually had the higher O_2 content, indicating that burner 2 and 4 had more air than burners 1 and 3. EER obtained samples from the coal ducts to burner 2 and 4, to check on the coal fineness achieved by mills A and B, respectively. The initial sample from burner 4 prior to classifier adjustment yielded 58 percent passing 200 mesh. After adjustments to both mills, mill A which feeds burner 2 produced coal with 69 percent passing 200 mesh while mill B (burner 4) achieved only 61 percent less than 200 mesh. The nominal design point is greater than 70 percent less than 200 mesh. Finally, burner 4 was inspected while mill B was off line to check for any obstructions or build up in or around the burner. Nothing significant was observed, with all passages, including the coal annulus, clear and no visible obstructions by slag outside the burner.

Foster Wheeler was consulted and two engineers were sent to WIPCO to evaluate the observed problems. Foster Wheeler personnel from the Test and Performance group obtained coal samples for fineness determination. The coal fineness measured by Foster Wheeler matched that determined by EER.

Since no apparent physical problems could be discovered, coal nozzles for burners 3 and 4 were retracted in a last attempt to improve stability. The flame signal did improve and the point of ignition for burner 4 moved adjacent to the exit. This adjustment increased stability sufficiently to permit staging the burners by opening the NO_x ports. However, burner 4 was still sensitive to the igniter retraction cycle. Discussions with the plant management revealed that the Forney service engineer may have trimmed the amplifier gain on burner 4 too much. After readjusting the amplifier, no additional problems with the indicated flame stability were observed and testing resumed on March 22, 1984.

4.7 Boiler Performance

The DMB's only significant effect on boiler performance was to increase the efficiency loss from unburned carbon. Operation with the NO_x ports open increased the unburned carbon loss more than when the ports were closed. There was no discernable effect on stack temperature, final steam temperature (FST), or boiler capacity when NO_x ports were closed. Excess air was usually higher when the NO_x ports were open, which increased stack temperature and decreased efficiency.

Slag accumulation on the front wall increased, adhering mainly to the refractory surfaces around the burners and NO_x ports. The remainder of the furnace stayed clean, except on a few occasions when the spot market coal WIPCO has been buying had extremely high iron content, causing the furnace hopper to bridge over.

The age of some of the equipment in the plant caused some minor problems with data acquisition. Steam flow readings were occasionally inconsistent. Usually feedwater flow was used since this is generally accepted as being more accurate, especially on older units. However, during some of the tests, feedwater flow was also apparently inaccurate. For example, during an eight hour test on 10/5/81, feedwater flow was indicated as being less than 150,000 lb/hr. while the generator was producing 20 MWG. At the same time, steam flow was indicated at 159,000 lb/hr. Both should have been showing about 180,000 lb/hr to produce 20 MWG for this unit. An accurate measure of steam flow is necessary for accurate boiler performance calculations.

The steam temperatures into and out of the desuperheater were also in doubt. With the desuperheater system turned off, these indications consistently showed a 20°F temperature rise. This made a detailed and accurate analysis of superheater performance impossible, since it was uncertain as to how each superheater section (primary and finishing) was performing.

4.7.1 Boiler Efficiency

The boiler efficiencies reported in this subsection are calculated values. Losses in efficiency include dry gas losses (stack temperature effect), moisture losses (water in both the air and fuel), unburned combustible losses, and radiation losses. Of the above, only dry gas losses and unburned combustible losses can be effected by the burner performance. The dry gas losses can also be affected by the fuel higher heating value. A certain amount of inaccuracy was introduced into the calculation since unburned combustible losses were not measured for every test.

As previously noted, the calculated boiler efficiency was the only measureable performance indicator that changed as a result of the DMB retrofit at WIPCO. Several representative test conditions for which complete boiler performance data was collected are summarized in Table 4-31. Tests A and B were conducted with the tertiary air ports closed. Tests C and D were conducted with the tertiary air ports open. In Test C, the burners were imbalanced resulting in high unburned combustibles. In Test D, the burner balance was improved reducing carbon loss.

The efficiency information generally indicates that the DMB operation increased the carbon loss and therefore decreased the boiler efficiency slightly. Table 4-32 compares the fuel analysis data for the coal samples collected during the tests shown in Table 4-31. There is negligible difference in the test fuels as far as the efficiency calculations are concerned.

4.7.2 Final Steam Temperature

One area of particular concern to the boiler manufacturer whenever modifications are made to the original firing system is that of final steam temperature impacts. If the modified or retrofit system changes the furnace outlet temperature, the distribution of heat absorbed by the various heat transfer sections of the boiler will change. A deviation from the design final steam temperature can cause a reduction in the electrical generating cycle efficiency and possibly damage the steam turbine.

Comparing firing system performance by studying final steam temperature can be difficult. Independent of the burner itself, changes in fuel quality and furnace ash deposits will also affect the steam temperature. The data collected during the DMB field evaluation program indicates that there is no significant impact on final steam temperature by the low-NO_x operation of the DMB. This conclusion applies to DMB operation both with and without the tertiary ports in operation.

TABLE 4-31. SELECT BOILER EFFICIENCY DATA

Test	Baseline Pre-NSPS Burners	A	B	C	D
Date	3/24/81	10/5/81	3/11/83	3/11/83	6/24/83
Steam Flow, lb/hr	180,000	180,000	182,000	180,000	180,600
Excess Air, %	25.4	18.0	22.4	19.3	26.5
Tertiary Ports	--	closed	closed	open	open
Efficiency Losses, %:					
Dry gas	6.308	5.527	6.121	5.973	6.478
H_2O from fuel	5.605	5.593	5.599	5.636	5.419
H_2O in air	0.158	0.138	0.153	0.150	0.162
Unburned comb.	0.370	0.660	0.730	3.060	1.070
Radiation	0.436	0.441	0.435	0.440	0.440
Mfr's Margin	1.500	1.500	1.500	1.500	1.500
Efficiency, %	85.622	86.141	85.461	83.242	84.932
Air Heater Gas Out, undiluted, °F	367	365	373	378	404
Steam Temp., °F	884	865	878	880	870
NO_x, lb/10^6 Btu	1.04	0.57	0.63	0.34	0.49
CO, ppm dry @ 0% O_2	36	137	32	105	34
HHV coal, B/lb	9,622	10,414	10,459	10,281	10,274

TABLE 4-32. FUEL ANALYSES

Test	Baseline Pre-NSPS Burners	A	B	C	D
Date	3/24/81	10/5/81	3/11/83	3/11/83	6/24/83
Ultimate, % by Wt:					
Carbon	54.10	56.64	58.53	57.77	57.73
Hydrogen	3.66	4.23	4.26	4.15	3.97
Oxygen	5.42	8.00	7.35	7.07	8.04
Nitrogen	1.00	0.83	1.10	0.91	1.18
Sulfur	3.82	3.84	4.00	4.64	3.58
Ash	27.97	13.39	11.93	12.29	12.55
Moisture	14.03	13.07	12.83	13.17	13.15
HHV, Btu/lb	9,622	10,414	10,459	10,281	10,274

4.7.3 Furnace Exit Gas Temperature

Table 4-33 presents the results of furnace heat absorption calculations based on the boiler performance data. The results suggest that the DMB yields a greater furnace psuedo emissivity (E), resulting in lower furnace exit gas temperatures and produces less fouling of convection surfaces (higher bank effectiveness factors, K_b) than does the old pre-NSPS turbulent burner.

An analysis of this nature on a unit with a boiler bank requires some assumptions since the boiler bank absorption cannot be determined directly from the data. In this instance the assumption made was that the K_b for the superheater and boiler banks were equal. This greatly increases the importance of the final steam temperature data and the assumption itself.

The steam flow data appears questionable. The electrical output of this unit during all of these tests was 20 MW; yet the data steam flow for test A was 147,800 #/hr as compared to approximately 180,000 lbs/hr for the other test. For this reason values appear in Table 4-33 for both steam flows for this test.

A decrease in FEGT would normally be expected to cause the FST to drop. The superheater surface is located at the furnace exit, therefore if the FEGT drops then heat transfer into the superheater will decrease from both reduced radiation and convection heat transfer. However, since the value of K_b apparently increased, due to cleaner surfaces in the superheater and boiler bank, the drop in FEGT was counter-balanced by this effect.

This analysis indicates that there is no significant impact on final steam temperature by the low-NO_x operation of the DMB. This conclusion applies to DMB operation both with and without the tertiary ports in operation. This observation would also tend to support the unmeasureable effect on final steam temperature by the DMB retrofit noted in subsection 4.7.2.

TABLE 4-33. FURNACE PERFORMANCE

Test	K_b	Steam Flow	FEGT	E	Burner
Base	.8993	180,000	1843.67	.2051501	Intervane
A	1.0805	147,800	1702.8	.2067696	DMB
A	1.2187	180,000	1717.58	.2495409	DMB
D	1.0011	180,600	1769.18	.254536	DMB

4.8 Furnace Corrosion Evaluation

There is always a concern that furnace waterwall tube surfaces will corrode at a higher rate whenever a low-NO_x firing system is applied to a power boiler. This concern is associated with the probability of those surfaces being subjected to reducing atmospheres as a result of the staged combustion process. The reducing environment accelerates wall corrosion and therefore shortens the usable life of the furnace wall.

A power boiler is considered to have a nominal life of 30 years. Corrosion rates that reduce the wall thickness of any tube below that which is necessary for the tube to withstand the design internal pressure become serious problems for the boiler operator. A single tube failure will require shutdown of the boiler and approximately 2 days to repair. If larger wall areas are affected, boiler outages of 2-4 weeks could be required for wall replacement.

The program host, Western Illinois Power Co-op, was willing to accept the DMB system without complete boiler restoration at the conclusion of the test program if it could be shown that the furnace corrosion rate had not increased since the retrofit. This attitude emphasizes the concern of the utility industry as a whole with respect to the corrosion problem.

A comprehensive evaluation of wall corrosion effects of the DMB firing system was included in the field evaluation program. The evaluation consisted of installation of four wall panel sections in the Pearl Station furnace for a period of 47 months and subsequently removing the panels, measuring metal loss, and performing a detailed metallugical examination of the tube surfaces. In addition, non-destructive tube wall thickness measurements were made periodically throughout the DMB test program at six different elevations on all four furnace walls. Based on the composite results of all of these tests, the DMBs had no impact on tube wastage. The results are summarized below and presented in detail in Appendix G of Volume 2.

4.8.1 Corrosion Panels

Corrosion panels represent the best method available to evaluate corrosion on a relatively short-term basis. It is also the most expensive approach. The use of corrosion panels involves the fabrication of actual sections of furnace wall. These sections, or panels, are carefully measured in the laboratory and then installed in the boiler during an outage. After a period of operation, the panels are removed, replaced with new wall tubes, and are then examined again in the laboratory. This panel approach to collecting tube wastage data is superior to the alternative approach, non-destructive ultrasonic measurements, for several reasons. One is that the measurement precision is much better in the laboratory than in the field. Another is that measurements made in the laboratory with micrometers are much more accurate than with ultrasonic instruments. Finally, by removing the tube panels, a detailed metallurgical examination of the tube wall material can be made to determine if microstructural changes are occurring regardless of wall thickness effects.

For the Pearl Station evaluation, four waterwall tube panels approximately four feet long and containing five 2.5 in. O.D. x 0.150 in. wall tubes were fabricated at the Foster Wheeler plant in Dansville, N.Y. and subsequently shipped to Livingston, N.J. where instrumentation was attached. The panels were fabricated from SA 178-A carbon steel, the standard material for waterwall surfaces in power boilers. Before installation at the WIPCO site, tube wall thicknesses were determined by micrometer at the ends and by ultrasonic techniques at 6 inch intervals along the entire length of the panel tubes on both the fireside and diametrically opposite side (180° away). Figure 4-41 is an illustration of one of the panels.

The panels were installed in 1980 in the locations shown in Figures 4-42 through 4-44. Follow-up ultrasonic measurements were made in 1981 and 1982 and finally, in 1984 (after 47 months of operation), the panels were removed and examined in the laboratory once again. All corrosion panel data, instrument descriptions, and additional tube photographs are presented in Appendix G of Volume 2.

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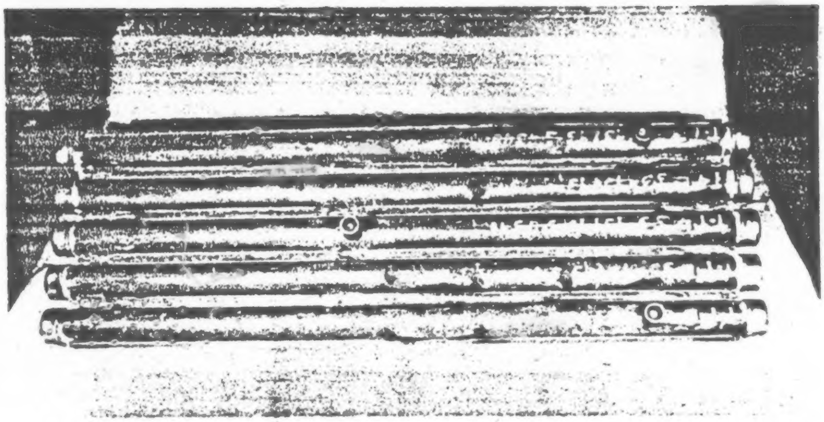

Figure 4-41. Typical corrosion panel.

PHOTOGRAPH 1/12X MAGNIFICATION PRE-TEST CONDITION

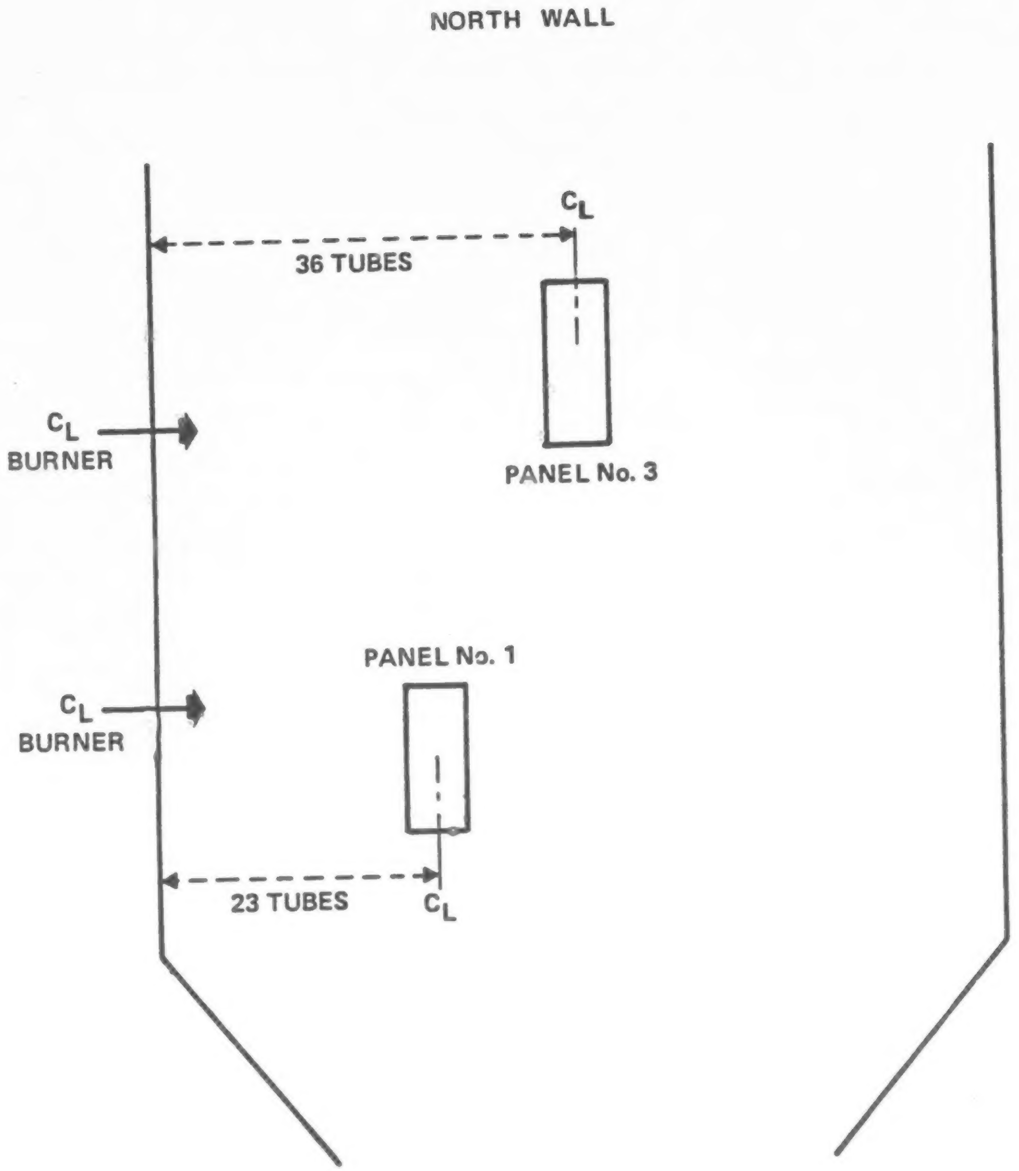
NORTH WALL
C_L
36 TUBES
C_L
BURNER
PANEL No. 3
PANEL No. 1
C_L
BURNER
23 TUBES
C_L

Figure 4-42. North wall - corrosion test panel locations.

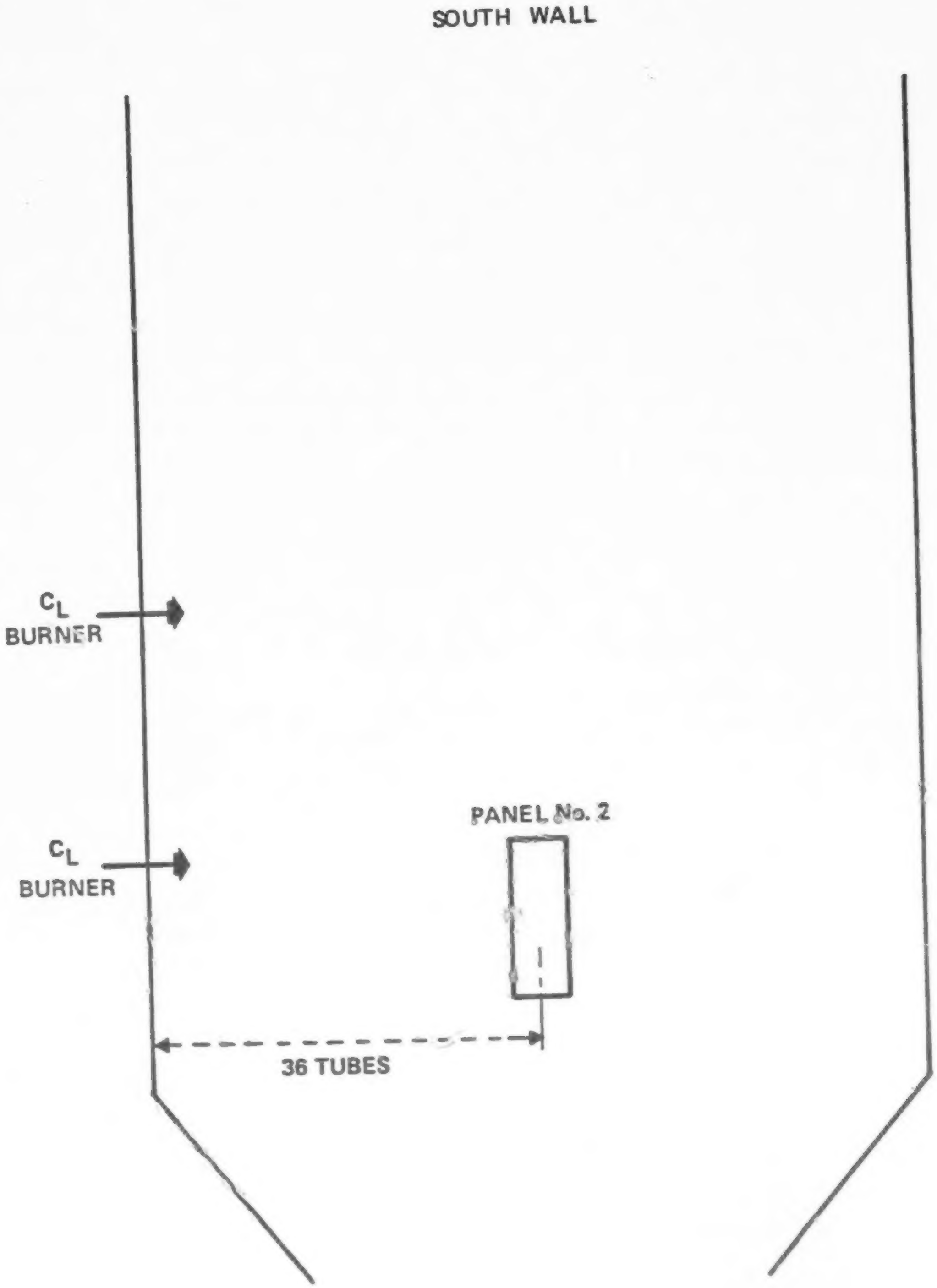
SOUTH WALL
C_L
BURNER
C_L
BURNER
PANEL No. 2
36 TUBES

Figure 4-43. South wall - corrosion test panel locations.

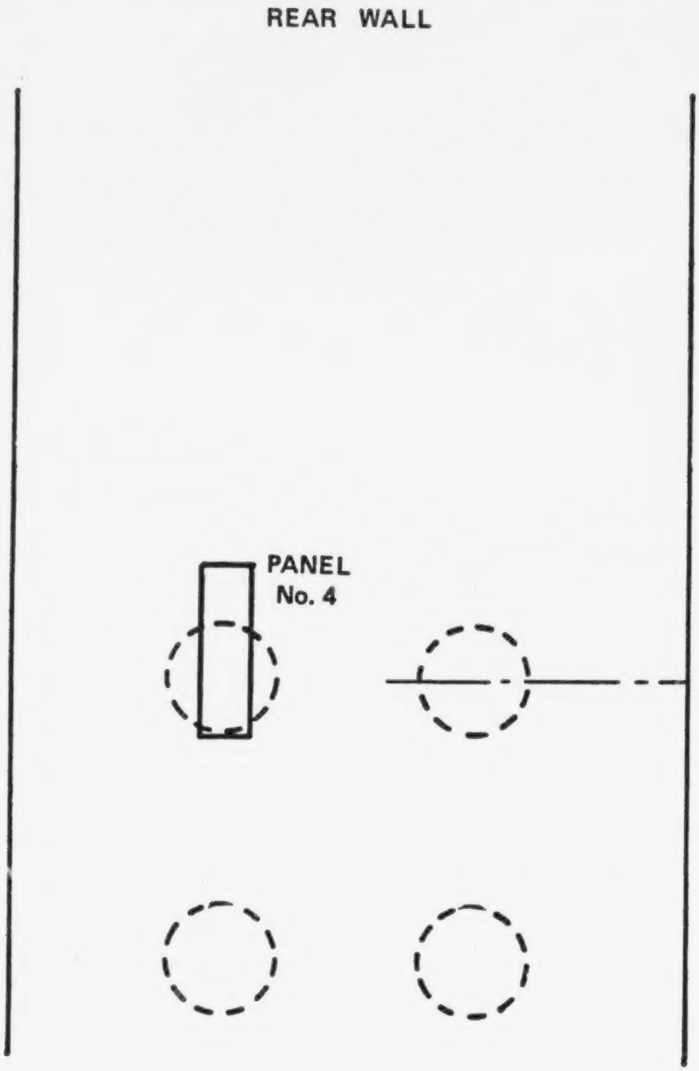
REAR WALL
PANEL
No. 4

Figure 4-44. Rear wall - corrosion test panel locations.

To determine the corrosion rate of each test panel, the mean tube wall thickness before exposure was compared to the thickness after exposure. In order to remove the effects of the shot blast cleaning method the metal loss measure on the cold side was subtracted from the hot side corrosion to obtain a net corrosion rate of the furnace. A Students' t test was performed on the data to provide some insight on the validity of results, but the analysis is moot considering the low net corrosion rates found. The results of the analysis is shown in Table 4-34.

Panels 1, 3 and 4 have corrosion rates on the furnace and cold sides that are almost identical while panel 2 shows a large difference between the furnace and cold side. The almost identical corrosion rates for panels 1, 3, and 4 can be attributed to either steam side corrosion or the shot blast cleaning; it cannot be determined which mechanism produced the corrosion but it is likely due to the cleaning process. The furnace side of panel 2 has an apparent corrosion rate that is consistent with the other panels while the cold side has a much higher corrosion rate that cannot be explained.

A Students' t analysis was performed to evaluate whether or not the mean tube wall thickness had changed after the 47 month exposure to furnace conditions. The null hypothesis is that the mean wall thickness had not changed; the alternate hypothesis is that the mean wall thickness had changed. For this analysis only paired measurements were used, those measurements that did not have a corresponding measurement after exposure were not included. It was also assumed that the standard deviations of the means compared were equal; this assumption is reasonable because the experimental and measurement error before and after is substantially the same. The Students' t under these assumptions takes the following form.

$$t = \frac{x_1 - x_2}{s\ 1/n_1 + 1/n_2}$$

and the pooled variance is

$$s^2 = \frac{(n_1-1)s_1{}^2 + (n_2-1)s_2{}^2}{n_1 + N_2{}^{-2}}$$

TABLE 4-34. CORROSION RATE OF TEST PANELS

		Mean Tube Wall Thickness, Mils							
Tube Side	Panel#	Before	After	Change	Students t	Degrees of Freedom	1-P(t)	Net Furnace Side Corrosion mpy	20 Years Loss, mil
FS	1	175.21	174.36	0.85	-1.145	8.2	0.872	0	0
CS		176.50	175.60	0.90	-0.971	78	0.833		
FS	2	174.71	174.07	0.64	-0.633	82	0.735	0	0
CS		176.51	174.15	2.36	-2.167	80	0.983		
FS	3	174.95	174.50	0.45	-0.464	82	0.678	+0.059	.119
CS		175.50	175.12	0.38	-0.333	78	0.678		
FS	4	177.05	175.33	1.72	-2.019	82	0.976	+0.016	0.323
CS		176.51	174.98	1.53	-1.484	80	0.929		

1-P(t) - Probability when accepting the null hypothesis

FS - Furnace Side

CS - Cold Side

and the degrees of freedom (d.f.) is

$$d.f. = n_1 + n_2 - 2$$

where:

t = Students' t

x_1 = mean wall thickness before exposure

x_2 = mean wall thickness after exposure

n_1 = number of measurements in x_1

n_2 = number of measurements in x_2

S_1^2 = variance of x_1

S_2^2 = variance of x_2

d.f.= degrees of freedom

Based on the Students' t analysis only two sides show significant corrosion levels at the 95 percent probability level. The cold side of panel 2 and the furnace side of panel 4 show a difference in thickness large enough to be statistically significant. This supports the conclusion that the panel corrosion rate is small since most of the changes in tube wall thickness are not significant.

When reviewing the raw data from the corrosion panels one will notice that in some cases the thickness of the tubewall increased over the four year exposure. This can be attributed to the following causes:

1. The exact location of the measurement cannot be duplicated. A small change in the measurement location will change the measurement.

2. The ultrasonic measuring device cannot be kept perpendicular to the tangent of the tube surface.

It appears that the increases in the tube thickness are indicative of the very minor corrosion found and the measurement errors described above.

4.8.2 Metallurgical Analysis

The metallugical analysis includes a visual examination, hardness surveys and microstructural examinations of furnace side and the opposite or cold side faces of the tube panels.

Visual examination showed the outside surfaces of test panel tubes were relatively clean and contained small quantities of loose scale and overlying corrosion products/deposits exhibiting various hues of white, tan, red, brown and black. Tubes in Panel No. 4 contained the least quantity of deposits while tubes in Panel No. 2 contained the most.

A photograph illustrating the appearance of one of the panels in the pre-test condition was shown in Figure 4-41. Photographs illustrating the post-test appearances of test panels in the as-received and in the grit-cleaned conditions are shown in Figure 4-45.

Photomacrographs illustrating the appearances of grit cleaned fireside surfaces of selected representative tubes in test panels 1 and 3 are shown in Figures 4-46 and 4-47. A typical photomacrograph illustrating tube O.D. and wall thickness measurements of sections cut from the top and bottom of tubes in panels Nos. 1 and 2 are shown in Figures 4-48. A photomacrograph illustrating the results of hardness surveys made around the circumferences of the same tubes is shown in Figures 4-49. A photomicrograph illustrating the representative microstructural appearance of the as-received tubing material in the post test condition is shown in Figure 4-50.

The visual and microscopic examinations, and the tube wall measurement data indicates that the panel tubes suffered insignificant metal wastage as a result of the four-year exposure in the test environment.

Anomolously, several of the more highly alloyed 310 stainless steel identification labels attached to the fireside surfaces of the test panel tubes suffered localized corrosive attack (see Figure 4-47). Weldments joining these labels were cracked allowing the labels to separate partially

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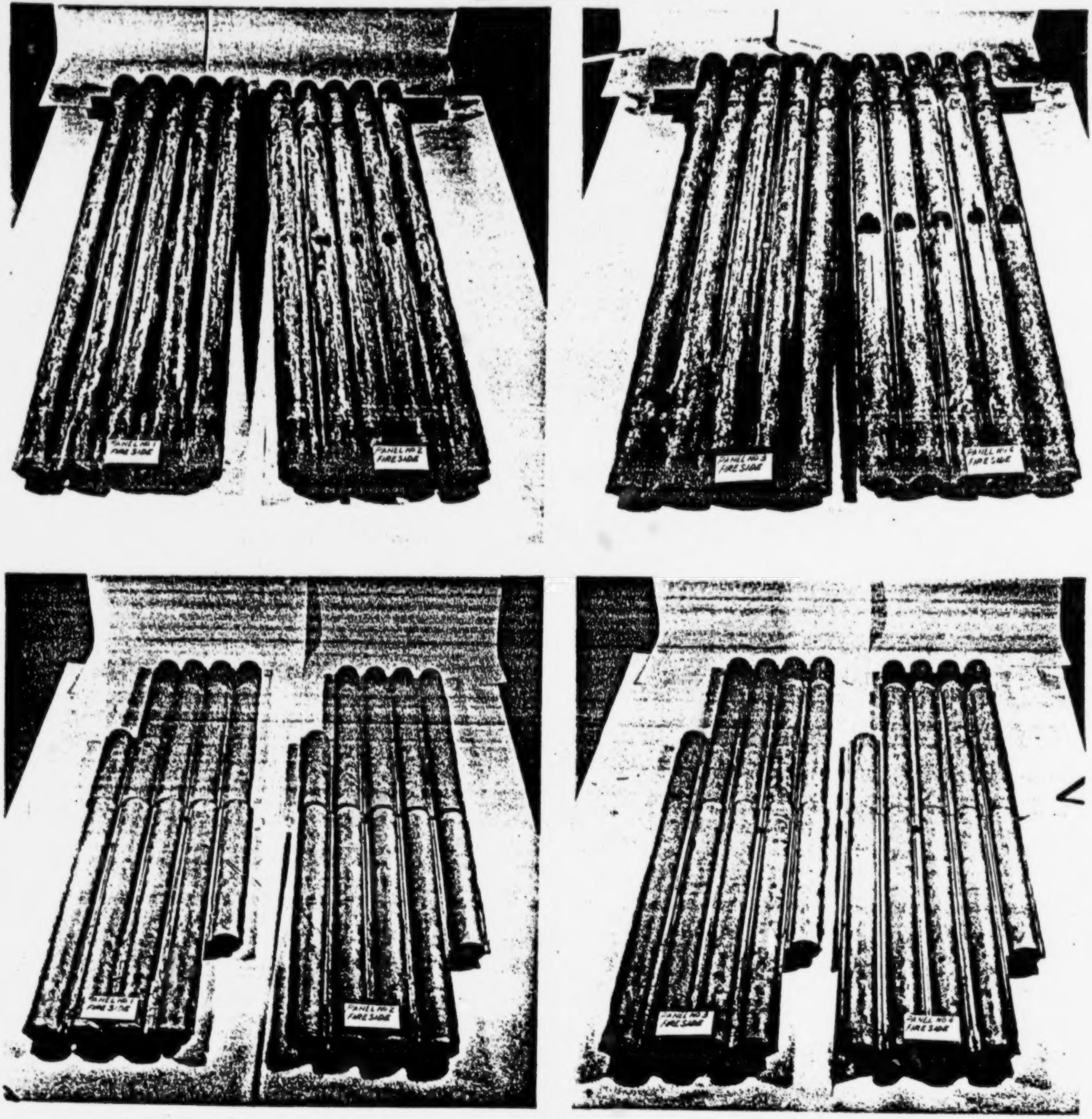

Figure 4-45. Corrosion panel photographs.

TOP: PHOTOGRAPH APPROX. 1/17X MAG. AS RECEIVED
BOTTOM: PHOTOGRAPH APPROX. 1/17X MAG. AFTER Al_2O_3 GRIT CLEANING

Photographs illustrate the appearance of the test panels in the as received (top) and grit cleaned conditions. Panels were cut in half to accommodate grit cleaning. Sections were cut from the top and bottom portions of tube numbers 1 and 5 in every panel for microscopic examination and hardness measurement.

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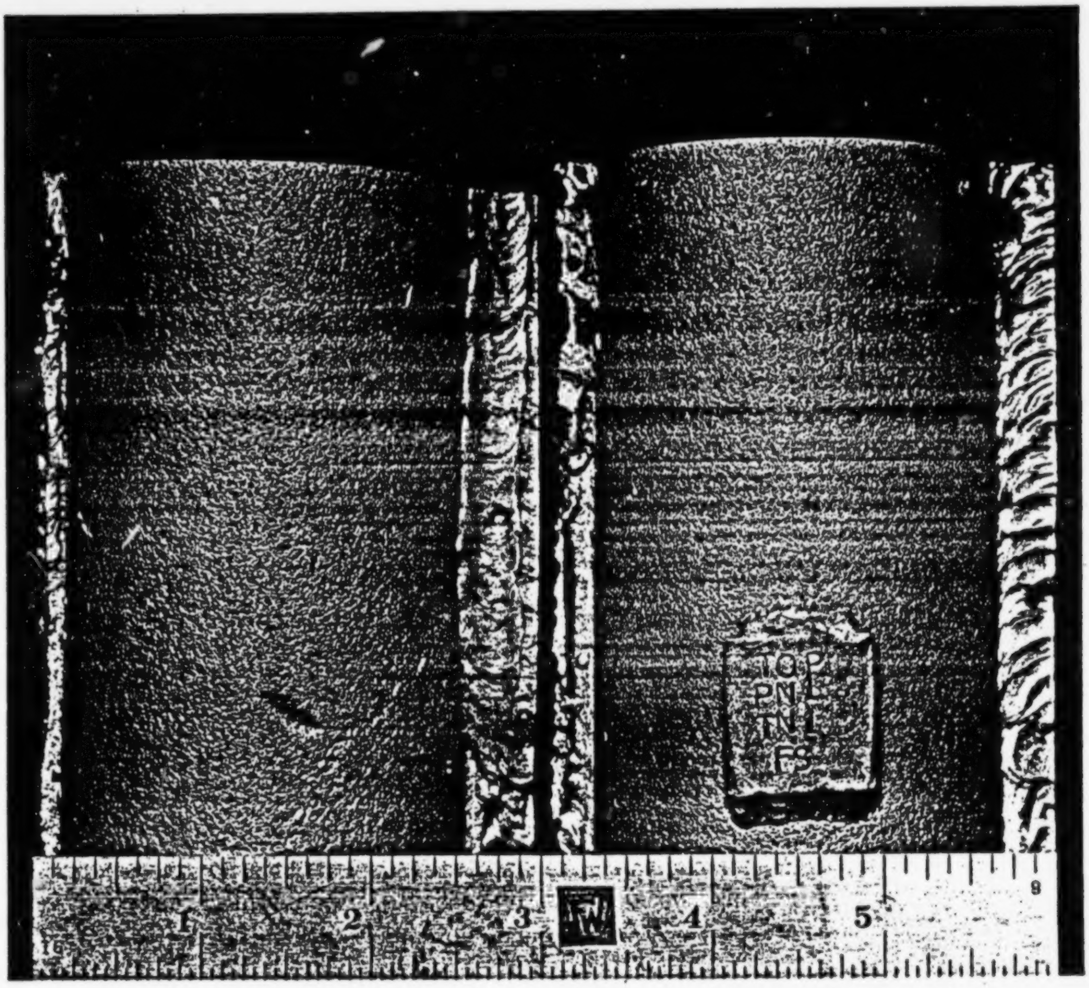

Figure 4-46. Corrosion panel photomacrograph (panel 1).

PHOTOMACROGRAPH 1X MAGNIFICATION AFTER Al_2O_3 GRIT CLEANING

LEFT: Cut section removed from bottom of tube No. 5 in Panel No. 1.
RIGHT: Cut section removed from top of tube No. 1 in Panel No. 1.

Photomacrograph illustrates the appearance of underlying fireside tube surfaces after corrosion deposits/scales were removed by grit cleaning.

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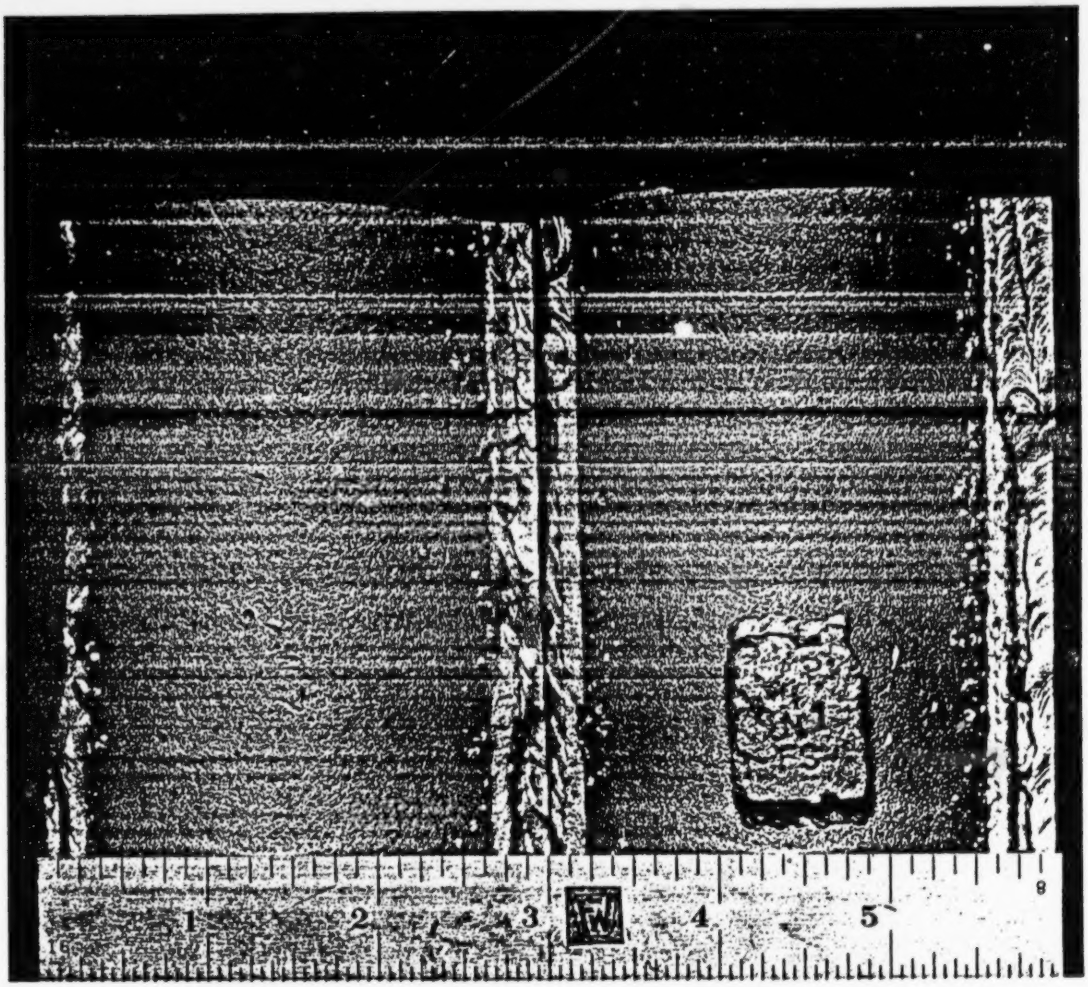

Figure 4-47. Corrosion panel photomacrograph (panel 3).

PHOTOMACROGRAPH 1X MAGNIFICATION AFTER Al_2O_3 GRIT CLEANING

LEFT: Cut section removed from bottom of tube No. 5 in Panel No. 3.
RIGHT: Cut section removed from top of tube No. 1 in Panel No. 3.

Photomacrograph illustrates the appearance of underlying fireside tube surfaces after corrosion deposits/scales were removed by grit cleaning. Notice localized corrosive attack occurring on 310 SS label.

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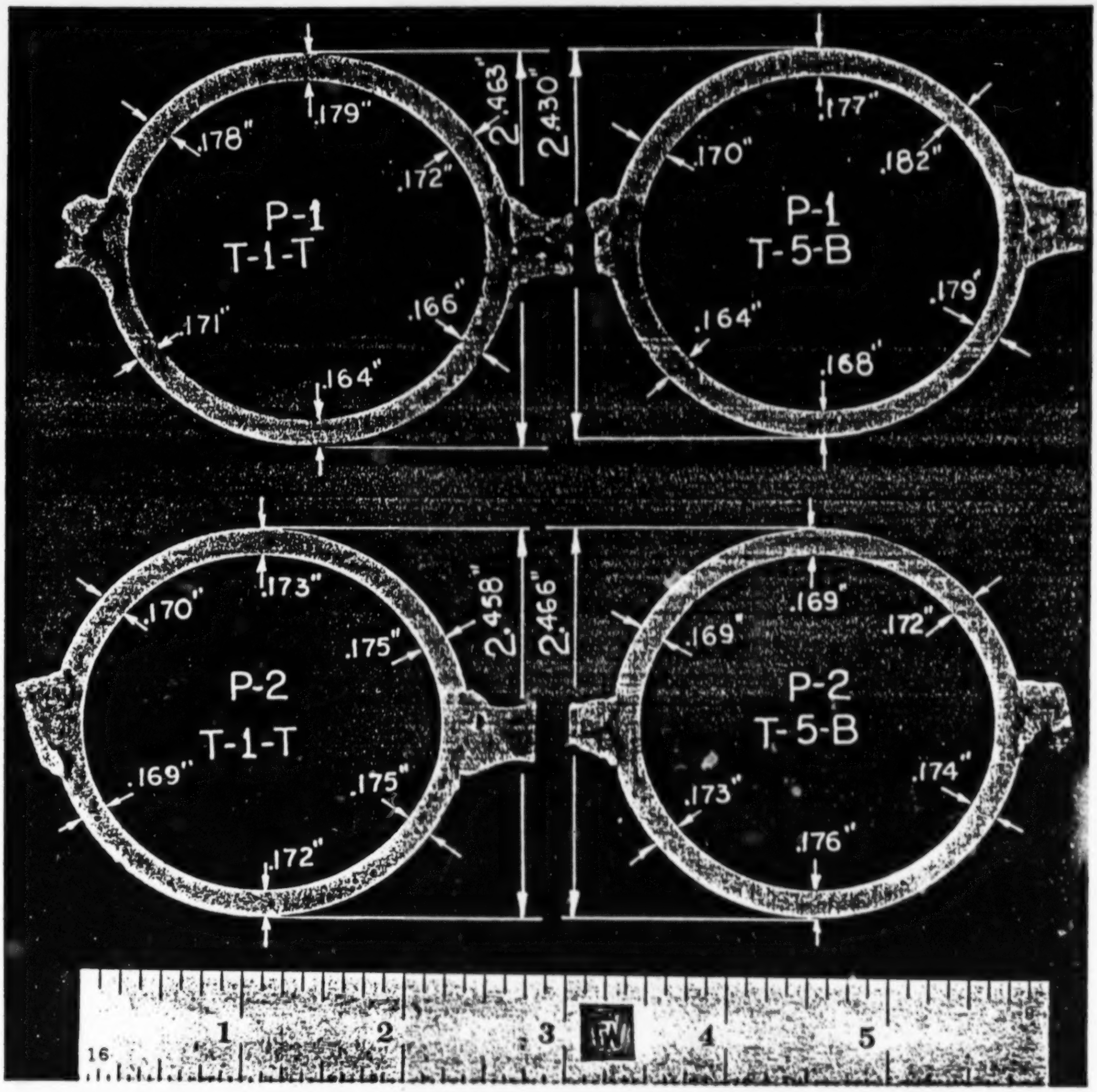
.179"
.178"
.172"
.171"
.166"
.164"
2.463"
2.430"
P-1
T-1-T
.177"
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.182"
.179"
.164"
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P-1
T-5-B
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.175"
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.172"
2.458"
2.466"
P-2
T-1-T
.169"
.169"
.172"
.174"
.173"
.176"
P-2
T-5-B
1
2
3
4
5
16

Figure 4-48. Corrosion panel photomacrograph (thickness).

PHOTOMACROGRAPH 1 MAGNIFICATION 10% NITAL ETCH

Photomacrograph shows the results of tube wall thickness measurements on transverse cross sections cut from the top and bottom portions of tubes 1 and 5 in Panels 1 (top) and 2 (bottom).

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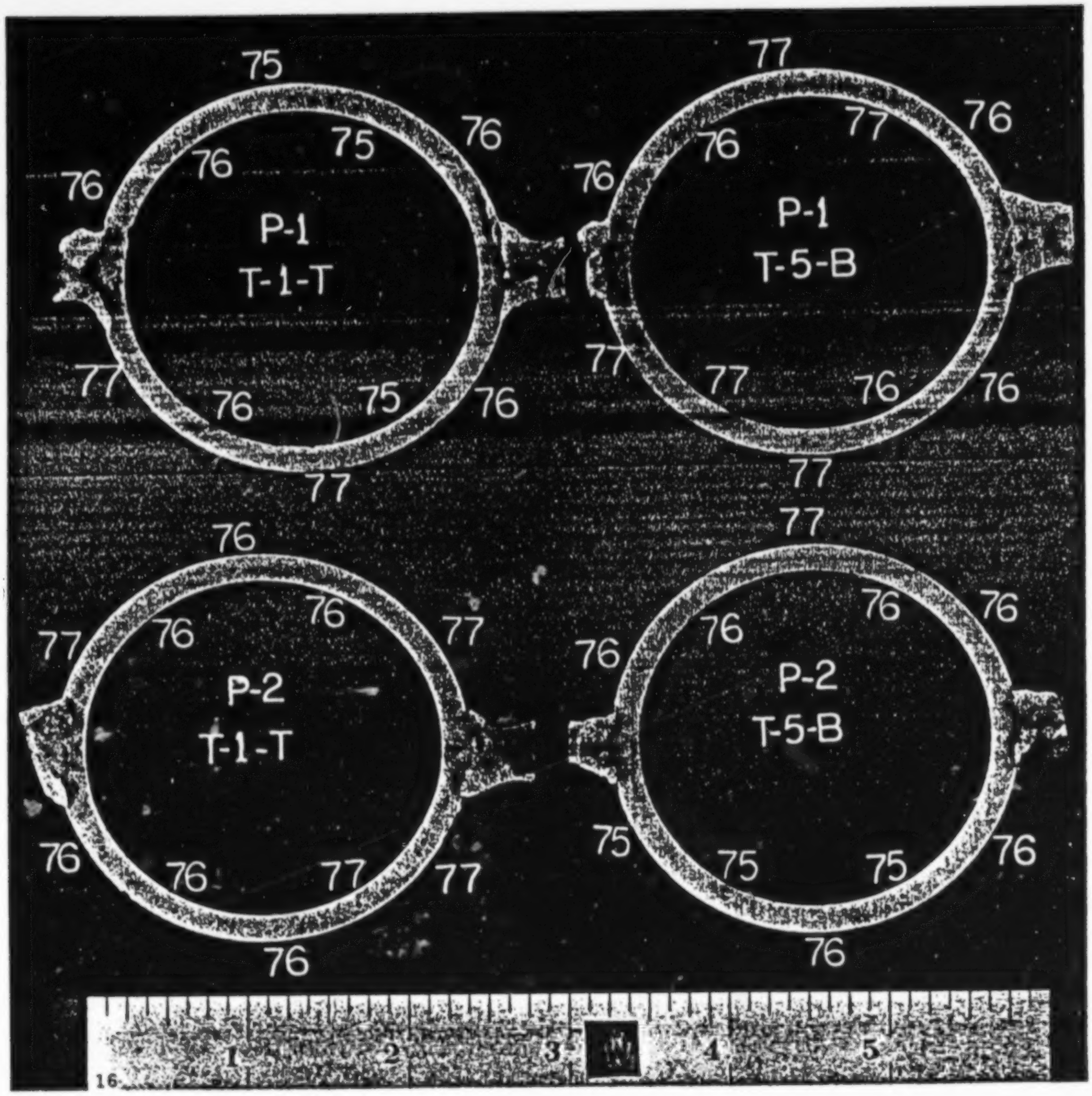
75
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P-1
T-1-T
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P-1
T-5-B
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P-2
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P-2
T-5-B
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75
75
76
76
16
1
2
3
4
5

Figure 4-49. Corrosion panel photomacrograph (hardness).

PHOTOMACROGRAPH 1X MAGNIFICATION 10% NITAL ETCH

Photomacrograph shows the results of Rockwell R_B hardness measurements on transverse cross sections cut from the top and bottom portions of tube Nos. 1 and 5 in Panels 1 (top) and 2 (bottom).

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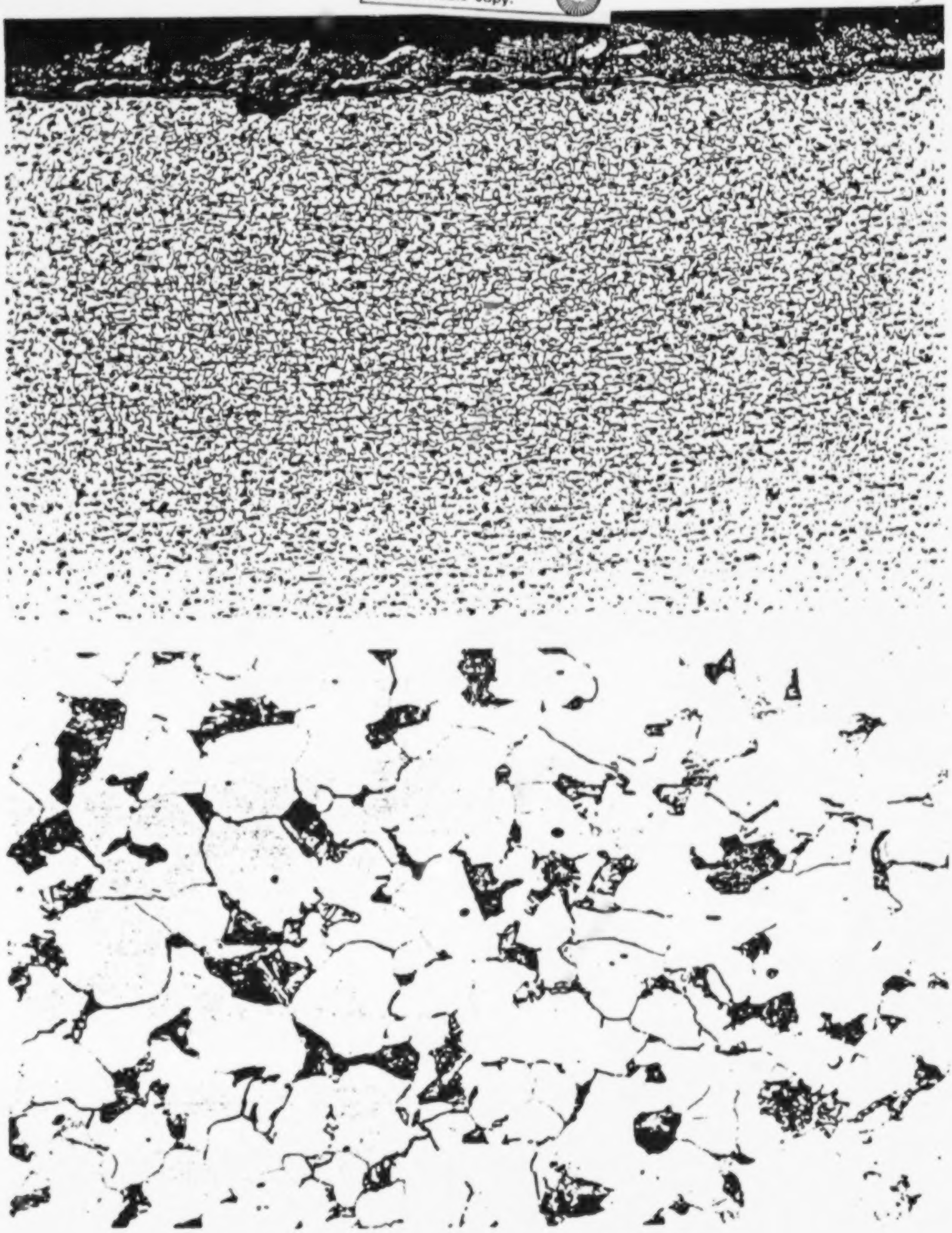


Figure 4-50. Corrosion panel photomicrograph.

TOP: PHOTOMICROGRAPH 100X MAGNIFICATION 2% NITAL ETCH
BOTTOM: PHOTOMICROGRAPH 1000X MAGNIFICATION 2% NITAL ETCH

Photomicrograph illustrates the representative transverse cross sectional microstructural appearance of tubing material (Tube No. 1 Fireside top, Panel 2). Microstructure is typical of as-received tubing material. The appearance of tenacious deposits and oxide scales is also shown.

from the water cooled tubes. The localized attack occurring on the uncooled sensitized 310 SS material indicates the environment is more corrosive at higher metal temperatures.

The highest measured tube wall loss was 0.010 inch (tube No. 5, panel No. 4). Paradoxically, this panel suffered the highest metal loss and contained the least quantity of occluded corrosion deposits.

The relatively moderate corrosive attack focused attention on the inherent reproducibility of the tube wall measurement methods which, in some cases, produced positive instead of anticipated negative valves.

The irreproducibility of the tube wall thickness measurement method is attributed primarily to the failure to pinpoint exact pre-determined locations for remeasurement; the configuration/contour of the measuring instrument contact points; tube surface irregularities and tube wall gradients existing around the tube circumferences.

While the precision of the tube wall thickness measurement technique was not established, values below ± 0.005 are considered insignificant for the reasons stated above.

4.8.3 Field Measurements of Furnace Wall Corrosion

During the course of the test program ultrasonic measurements were made of the furnace walls. These measurements were taken at five outages as follows:

May - 1980	Baseline and Installation of Corrosion Test Panels
May - 1981	Installation of Burners
April - 1982	Scheduled Outage
November - 1982	Scheduled Outage
April - 1984	Corrosion Panel Removal

The wall thickness was measured at six levels on all four walls and at the corrosion test panel. The locations of the elevations of the measurements are shown in Figure 4-51.

The measurements were taken at these times to compare the corrosion rate under different operating conditions. The period from May, 1980 to May, 1981 represents operation with the original burners. The period from May, 1981 to April, 1982 and April, 1982 to November, 1982 represent unstaged burner operation with the new burners. Finally, the period from November, 1982 to April, 1984 represents staged operation.

The measurements were made using an ultrasonic thickness measuring instrument. The measurements were made with two different instruments as follows:

5/80,5/81, 4/82	Krautkramer Branson DMI-B (See Appendix G)
11/82, 4/84	Digisonic 502 (See Appendix G)

The Krautkramer Branson was accurate to 5 mil while the Digisonic was accurate to 1 mil. Before the baseline measurement the furnace walls were and blasted to remove any accumulated deposits either from combustion or corrosion. before each subsequent measurement, the measurement locations were wire-brushed to minimize excessive removal of tube metal.

In comparison to the laboratory measurements made on the test panel the potential for measurement error is much greater for the field measured data. The sources of error include a less precise instrument, a change in instrument used, field conditions i.e. hanging from the ceiling on a rope supported scaffold in a dirty furnace, and finally inability to duplicate the exact measurement spot from year to year. The raw data is compiled in Appendix G of Volume 2. The data is also presented in Appendix G in a smoothed form. The smoothed form is presented because data in the raw form is almost unreadable.

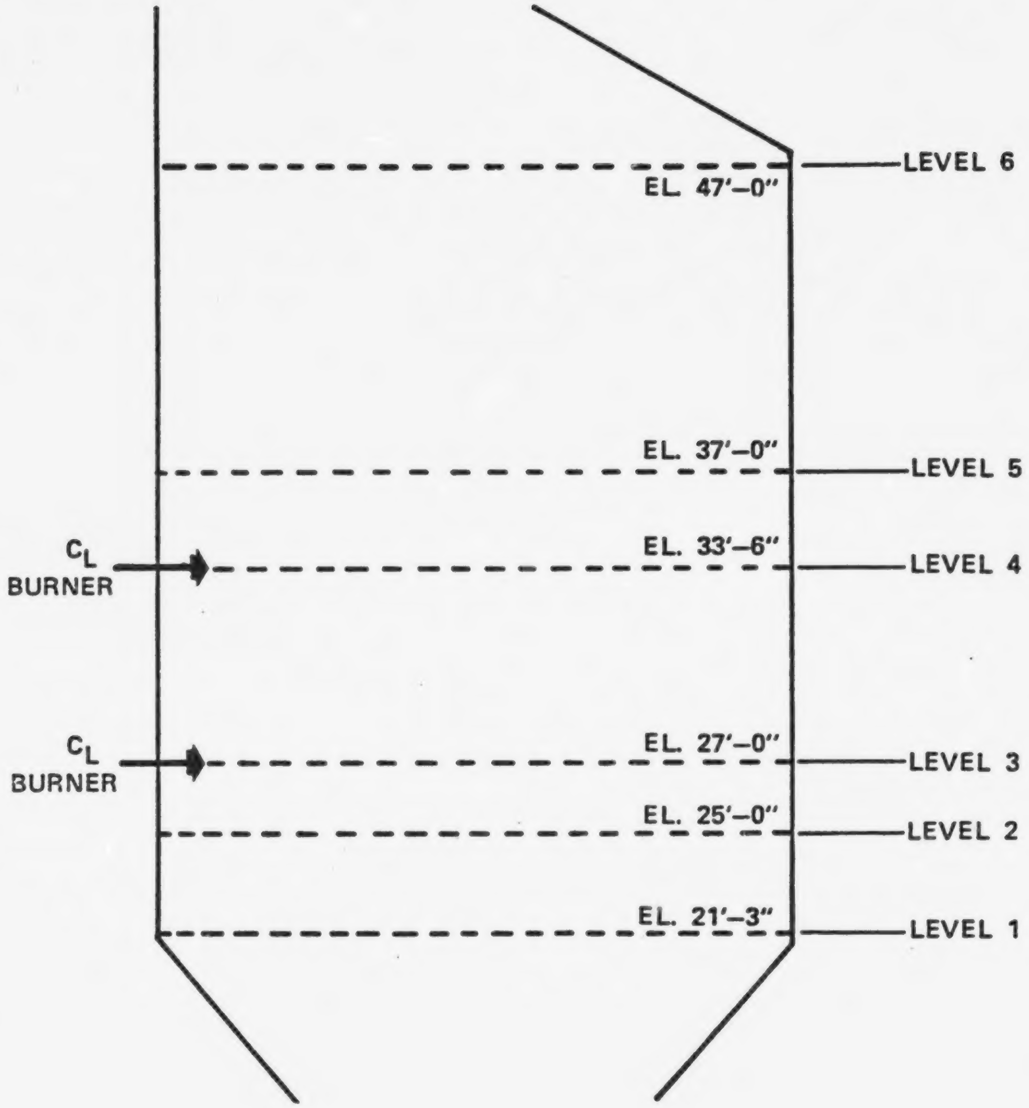

LEVEL 6
EL. 47'–0"
EL. 37'–0"
LEVEL 5
C_L
BURNER
EL. 33'–6"
LEVEL 4
C_L
BURNER
EL. 27'–0"
LEVEL 3
EL. 25'–0"
LEVEL 2
EL. 21'–3"
LEVEL 1

Figure 4-51. Elevations of furnace tube wall measurements.

After reviewing the field data it became obvious that the 1981 measurements on the rear wall levels 1-4 and the 1980 measurements on the rear wall level 5 are outlyers. Because of the large number of outlyers in the 1981 data set the whole set was questioned and not used for any further analysis. The 1980 set was still included in further analysis. Further, one can see that for the front wall levels 2, 3 and 4 the data is sparse because of all the perforations of the burners and the NO_x ports. The front wall data is also missing the baseline measurements taken in 1980 because the front wall was replaced during burner installation in the spring of 1981.

In order to better show some of the trends that are occurring, the data was plotted as the change in wall thickness from the 1980 baseline, and is shown in Figures 4-52 through 4-55, each figure showing all six levels of measurement on each wall. The only pattern of potential corrosion along a wall occurs on the south wall levels 2-5 at or about 20 tubes from the front wall. But the change was measured only between Spring of 1980 to Spring of 1982 after that no consistent loss in tube thickness is recorded. This pattern is too close to the front wall to be caused by flame impingement. Flame impingement on the side walls is seen, if it exists, about two thirds from the front wall. Directly opposed on the North wall the pattern is repeated, although not as clearly, again it is about 20 tubes out from the front wall. There is not pattern of corrosion at the burner levels on the rear wall indicating flame impingement.

No pattern of change in the corrosion rate was seen as the boiler operation was changed. This conclusion is consistent with the results of the test panels where no corrosion was seen.

Regression Analysis

A regression analysis of the furnace wall data was performed to see if some trend or pattern could be observed. The results of the analysis is seen in Table 4-35. A significant correlation showing a real corrosion rate was indicated on levels 1, 3 and 6 of the North wall; 1-4 on the South wall and 1, 5 and 6 of the rear wall. The largest corrosion rate was seen on the rear

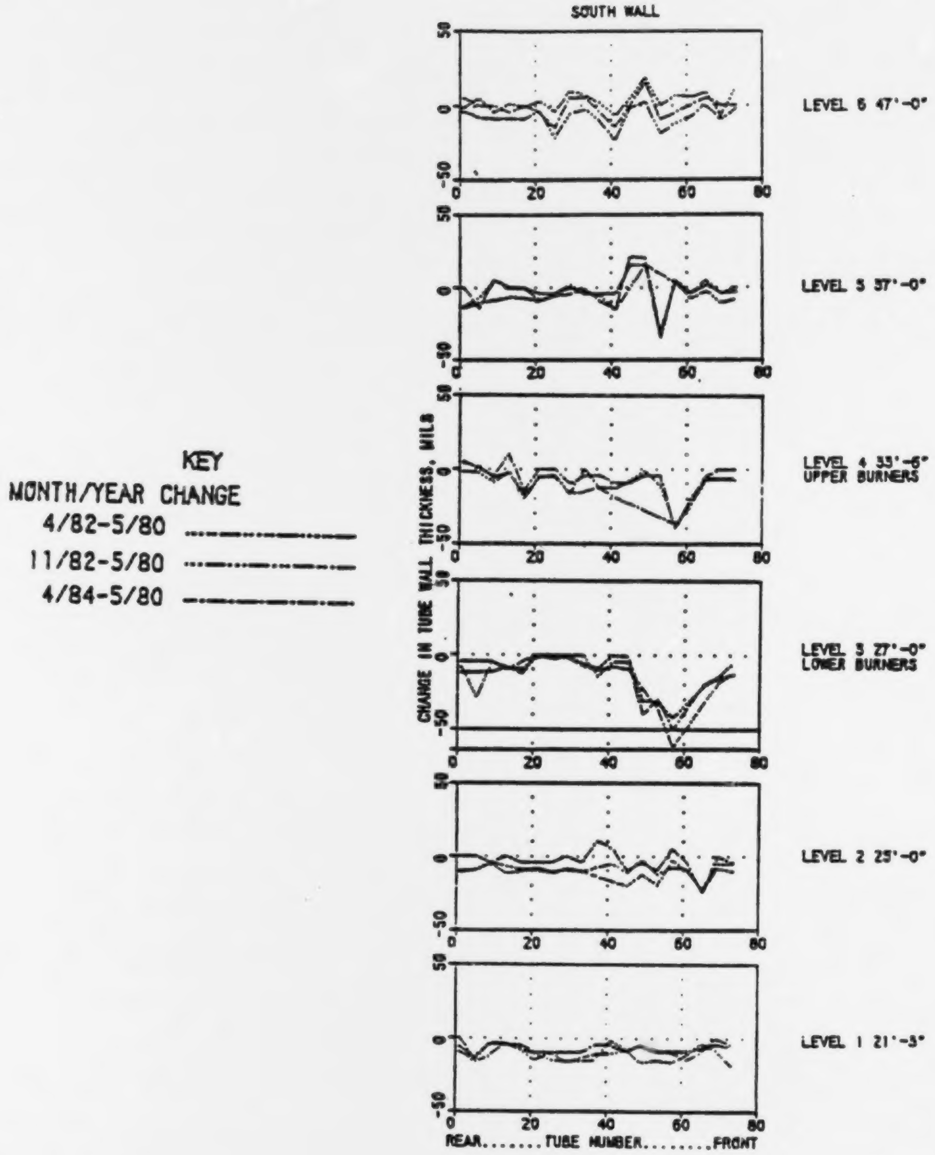


Figure 4-52. Change in tube wall thickness, south wall.

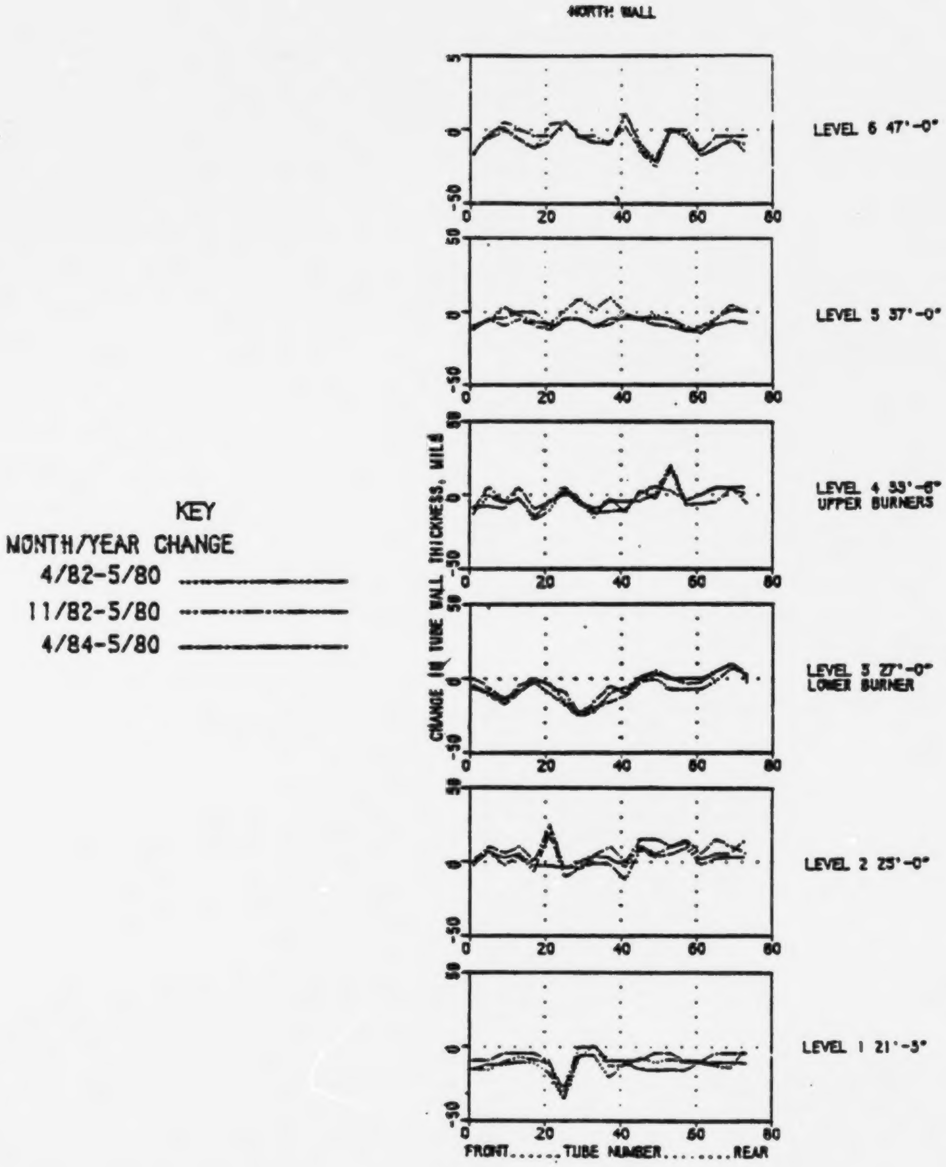


Figure 4-53. Change in tube wall thickness, north wall.

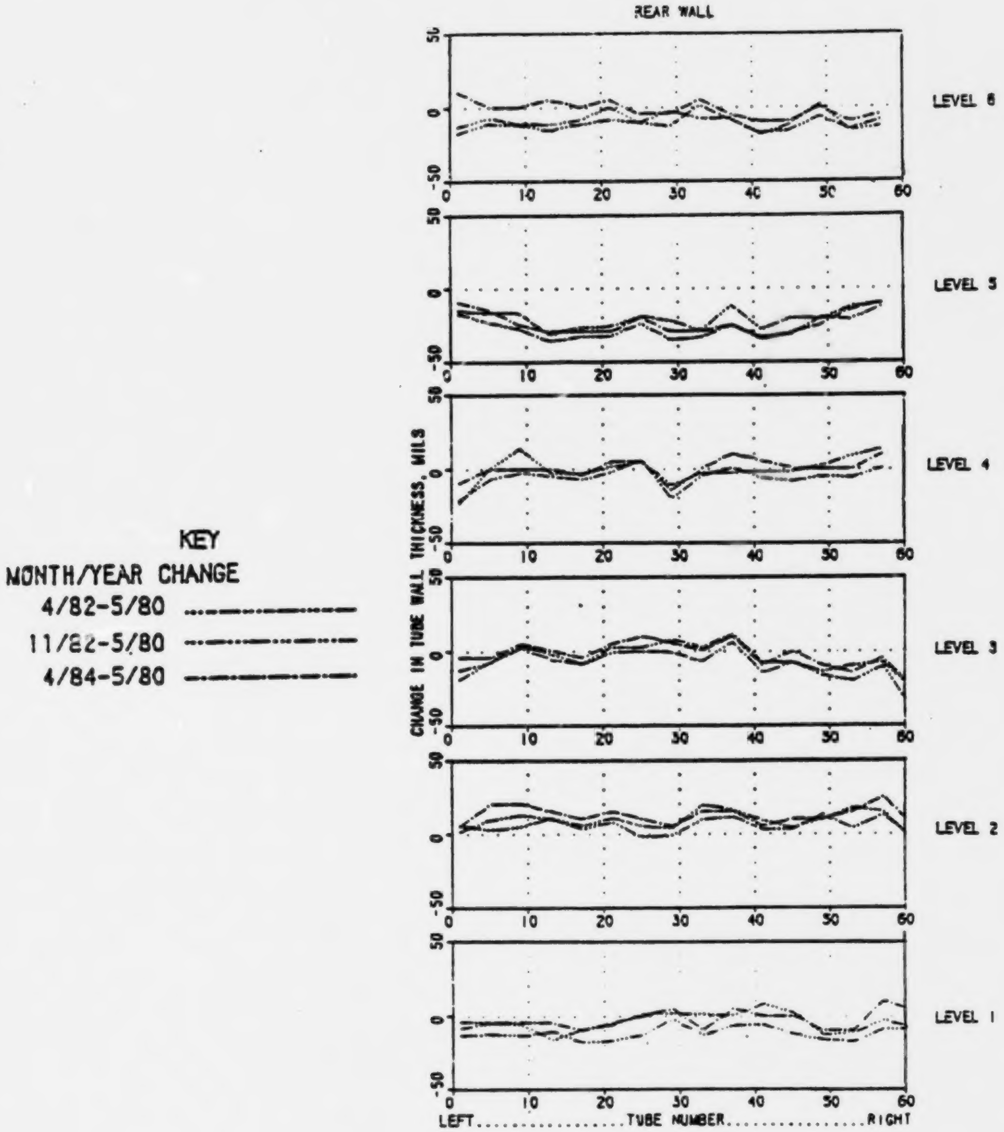


Figure 4-54. Change in tube wall thickness, rear wall.

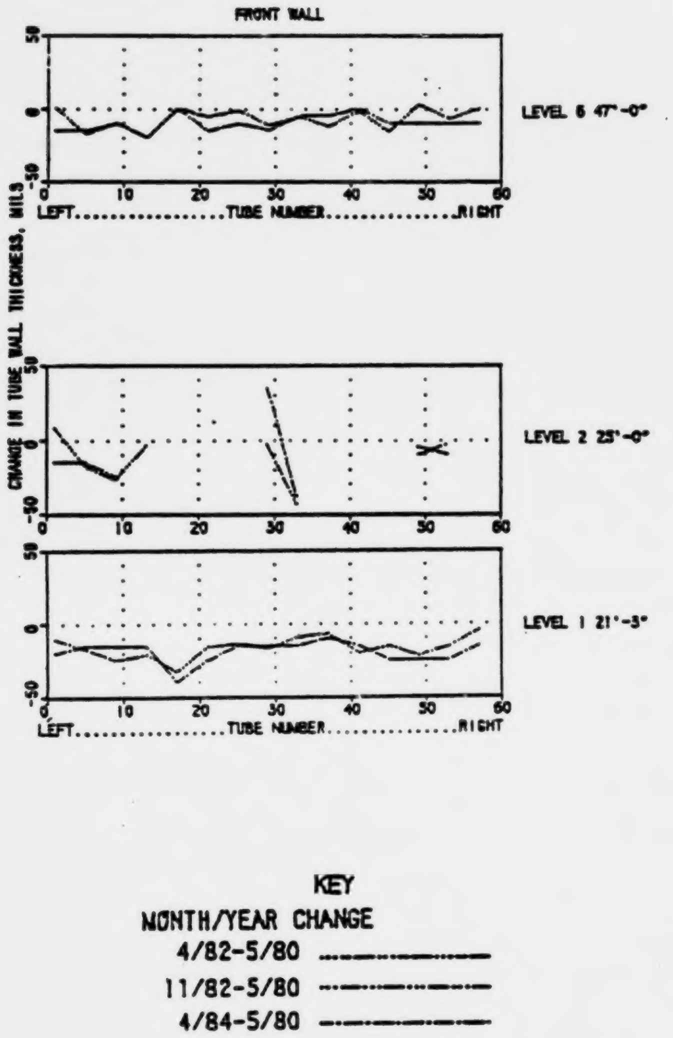


Figure 4-55. Change in tube wall thickness, front wall.

TABLE 4-35. REGRESSION ANALYSIS OF FURNACE WALL CORROSION DATA

WALL	LEVEL	MILLS/YR	R2*	DF*	A LEVEL*	SEE	INTERCEPT
North	1	-3.3	0.70	74	.01	4.79	170.77
	2	+.82	0.23	66	-	4.90	160.22
	3	-1.4	0.37	58	.01	4.95	167.153
	4	-1.01	0.20	70	-	7.21	169.52
	5	-0.95	0.19	74	-	6.86	169.59
	6	-1.8	0.36	70	.01	6.60	170.05
South	1	-2.69	0.64	74	.01	4.54	169.92
	2	-2.99	0.65	66	.01	4.94	171.12
	3	-3.17	0.50	62	.01	7.84	173.28
	4	-3.11	0.57	62	.01	6.30	172.32
	5	-0.88	0.224	66	-	5.48	167.21
	6	+0.32	0.057	74	-	7.79	168.17
Rear	1	-1.52	0.34	58	.01	5.95	171.91
	2	+2.14	0.48	58	.01	5.53	157.09
?	3	+1.86	0.19	58	.01	5.59	158.72
	4	+0.83	0.44	58	-	6.36	161.79
	5	-5.61	0.66	58	.01	9.14	180.76
	6	-2.72	0.51	58	.01	6.59	174.61

* R^2 is the coefficient of Correlations

DF is degrees of freedom

A Level is the level of significance of R^2 from reference 3

SEE is the standard error of the estimate wall at level 5 which as was mentioned contained very high thickness readings in the baseline measurements. Two levels, rear wall levels 2 and 3 showed significant increase in tube wall thickness, these two cases also show a large difference from the other levels in the magnitude of the intercept indicating an unusually low baseline measurement.

5.0 COMPARISON OF PROTOTYPE AND FIELD OPERATING DMBs

The prototype DMB design chosen for installation and demonstration at the WIPCO Pearl Station boiler had to be capable of stable operation, compatible with the boiler design, while producing low NO_x emissions. Since the DMB design was to be based on the results of tests in a research furnace, the LWS, some assurance was required that these test results could be used to predict the performance of the prototype DMB to the field unit. Though indirect, the approach taken was to evaluate the operating characteristics of the original burner design used at WIPCO in the LWS, the Foster Wheeler Intervane burner, and compared the results with field experiences. Similarity of the research furnace and field results would then be an indication that the operating characteristics of the DMB in the LWS and the WIPCO boiler would also be similar.

Comparison of the observed performance for the Intervane burner in the LWS and at the WIPCO unit revealed both similarities and differences. The qualitative performance characteristics were similar. Flames produced by the baseline burner were short, bright, intense, and stable for both tests. The range of operation was somewhat greater in the LWS tests. The base of the flame could be moved into the furnace by varying register and core air valve positions. The range of register adjustment in the field test was restricted to ± 5 percent from the baseline setting because of the sensitivity of flame standoff distance. Opening the registers caused the flames to move into the furnace and resulted in a loss-of-flame indication from the scanners.

The quantitative measures of the Intervane burner performance in the LWS and at WIPCO, NO_x and CO emissions, were different. In the LWS under comparable conditions, CO emissions were about 200 ppm compared to less than 50 ppm during the field test. This difference can be attributed to the colder thermal environment of the old LWS quenching CO oxidation reactions in the upper furnace. The NO_x emissions, however, were considerably lower in the LWS than those measured during the baseline boiler tests. This difference is again due in part to the same thermal environment effect that impacted CO emissions, but to a much lesser degree. Differences in burner design and operating conditions probably had a greater effect, as discussed in Section 3.1.3.

The LWS performance of the DMB design chosen for installation at the WIPCO unit, the DMB with Foster Wheeler parameters, was compared with the requirements of the boiler prior to retrofit to verify acceptability. This comparison, discussed in detail in Section 3.4.5 is summarized in Table 5-1. In general, LWS performance of the DMB met the WIPCO boiler requirements. The DMB installation at WIPCO was a 4-burner array with the combustion air supplied to a common windbox. The operation of such a system is considerably more complex than for a single burner in a research facility such as the new LWS. In addition, the similar geometry and dimensions of the LWS and the WIPCO boiler result in a significantly different furnace environment for the single burner LWS system and the multi-burner field unit. This section compares the actual performance of the DMBs at WIPCO with the single burner, LWS DMB tests.

5.1 Emissions

The emissions levels achieved in the WIPCO boiler with the DMBs are summarized is Figure 5-1. This figure represents a cross plot of data for two excess air ranges, since it was not possible to vary burner zone stoichiometry independently. These data were not obtained at fixed burner settings and thus, are not strictly comparable to the prototype DMB LWS test results included in the figure. In particular, burner zone stoichiometry was dependent on burner adjustments because of the common windbox installation. However, the data does indicate a degree of similarity in the levels of both NO_x and CO emissions which could be achieved for conditions, which minimized NO_x in the LWS and the WIPCO boiler. NO_x emissions were more sensitive to burner zone stoichiometry for the WIPCO burner array than the prototype burner in the LWS. This effect is probably due in part to the different burner settings that produced the range of burner zone stoichiometries as well as any differences in furnace characteristics.

TABLE 5-1. COMPARISON OF FOSTER WHEELER PROTOTYPE DMB LWS PERFORMANCE WITH WIPCO BOILER REQUIREMENTS

Parameter	Requirement	LWS Performance
Flame Shape	Compatible with host furnace	Flame length: 19 ft
Flame Stability	Stable over host load range	Minimum load less than 50% MCR*
	Insensitive to burner settings	Stability insensitive
Ignition	Compatible with commercial system	Confirmed
Flame Scanning	Compatible with commercial system	Confirmed
Pressure Drop	Less/equal to host burner	1.5 to 2.5 in H_2O
Efficiency	Equal/better than host burner	Carbon in ash = 2.3 - 11.0%
Tertiary Ports	Locations compatible with host furnace	Ports redesigned for field evaluation
Control System	Compatible with commercial standards	
NO_x	Program goal: 0.2 lb/10^6 Btu	0.22 lb/10^6 Btu at design point. Sensitive to excess air and burner zone stoichiometry. Insensitive to load

*Maximum Continuous Rating

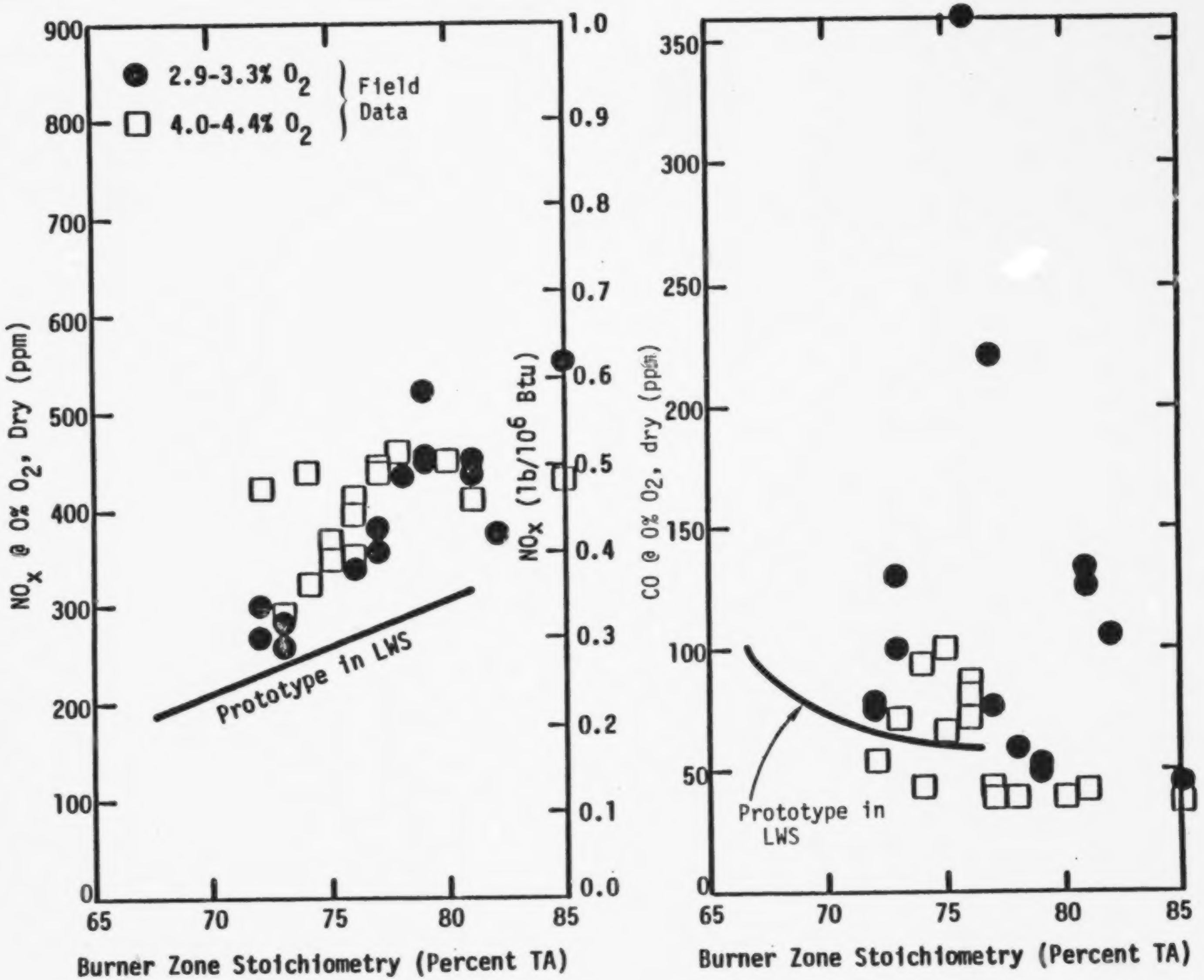


Figure 5-1. Comparison of staging effect on DMB performance in the LWS and WIPCO.

The CO emission characteristics, indicative of combustion efficiency, had a much wider range in the field boiler than for the single burner LWS tests. CO emissions were generally lower at high burner zone stoichiometry for the WIPCO tests than in the LWS. This is a result of the hotter thermal environment at WIPCO yielding higher CO oxidation rates. However, the CO emissions at WIPCO spanned a wide range indicating much greater sensitivity to operating conditions. As discussed in Section 4.5, in a multi-burner array such as at WIPCO unbalanced air distribution under staged conditions would result in each burner operating at different conditions with the overall performance in terms of CO and NO_x emissions being an average of the individual burners. Since NO_x emissions are essentially linear with respect to burner zone stoichiometry, no significant impact of the maldistribution would be expected. However, if a burner in the array were operating at a burner zone stoichiometry below the characteristic CO knee as a result of the maldistribution, the average CO level would be greatly increased.

The operating condition selected for the second thirty test period beginning August 27, 1983 utilized settings for each burner very similar to the optimum condition defined during the LWS tests of the Foster Wheeler prototype DMB. These settings are compared in Table 5-2. These WIPCO settings produced NO_x emissions of 383 ppm with 46 ppm CO at 20 percent excess air and an overall burner zone stoichiometry for test condition 50.01 on August 25, 1983. Measurements across the backpass verified balanced air distribution. For the same excess air and degree of staging, the Foster Wheeler prototype DMB in the LWS yielded about 250 ppm NO_x and 170 ppm CO. The difference in CO levels can be directly related to furnace thermal environment. The "hotter" WIPCO boiler is more conducive to CO oxidation than the single burner LWS. In addition this low level of CO is similar to the level achieved during the 30-day baseline test of the Intervane burners, 37 ppm. The large difference in NO_x emissions is probably indicative of the complexity of a multi-burner system in addition to any effects of thermal environment. The demonstrated sensitivity to air distribution, the interacting flames, and complex flows within the boiler would also contribute to differences between the WIPCO installation and the single burner LWS

TABLE 5-2. COMPARISON OF OPTIMUM FOSTER WHEELER PROTOTYPE DMB CONDITIONS TO SECOND THIRTY DAY TEST SETTINGS

VARIABLE	FW PROTOTYPE OPTIMUM	BURNER SETTINGS			
		WIPCO BURNER NO.			
		1	2	3	4
Nozzle Position, in from baseline	0	0	0	0	0
Core Air Valve, ° Open	45	45	45	45	45
Inner Register, ° Open	15	10	10	10	10
Outer Register, ° Open	15	20	10	20	15
Inner Sleeve, % Open	100	50	50	50	50
Outer Sleeve, % Open	100	50	50	50	50
NO_x Ports, % Open	All ports 100% Open				

system. Indeed, optimum conditions in the research facility may not necessarily produce the lowest emissions in a multi-burner unit.

5.2 Operation Characteristics

The operation characteristics of the DMBs installed at WIPCO and the Foster Wheeler prototype DMB tested in the LWS were generally similar. Performance criteria are compared in Table 5-3. Flame shape was somewhat more variable and sensitive to burner adjustments in the WIPCO boiler. This is probably because changes in burner settings affect the air distribution through the common windbox. For all burner adjustments during the LWS tests of the Foster Wheeler prototype DMB, the ignition point remained 12-18 inches from the burner exit. In the field this was much more variable, with the base of the flame moving from within the burner exit to 3 feet from the front wall of the boiler. This variability in ignition point did not affect the stability of the flames as indicated by flame scanner signals. The flames were also observed to roll to one side, both in the LWS and at WIPCO. For example, the flame from burner 4 tended to roll along the adjacent south wall. This behavior was observed for the Intervane burners as well as for the DMBs. In the LWS, the flame tended to veer toward the opposite right corner of the LWS. This may be a characteristic of the Foster Wheeler burner design in general or perhaps some misalignment during installation in each case.

The DMBs at WIPCO maintained stability under staged conditions over the entire two-mill operation load range, 13 - 20 MW. Stability was demonstrated to less than 50 percent maximum continuous rating (MCR) during the LWS testing. A commercial ignition/flame safety system similar to that used at WIPCO was used during the LWS testing to confirm compatibility with commercial standards. Problems with flame detectability occurred only briefly during the WIPCO tests when signal amplifiers were out of adjustment. Also confirmed was acceptable windbox to furnace pressure differential that permits both unstaged and staged operation within the capabilities of the existing WIPCO fan system.

TABLE 5-3. COMPARISON OF DMB OPERATIONAL CHARACTERISTICS IN THE LWS AND WIPCO PEARL STATION

PARAMETER	REQUIREMENT	LWS PERFORMANCE	WIPCO PERFORMANCE
Flame Shape	Compatible with host furnace	Length = 19 ft.	Length 17-20 ft.
Flame Stability	Stable over host load range	Minimum load 50% MCR	Stable over host load range
	Insensitive to burner settings	Stability insensitive	Generally insensitive
Ignition	Compatible with commercial system	Confirmed	Confirmed
Flame Scanning	Compatible with commercial system	Confirmed	Confirmed
Pressure Drop	Less/equal to host burner	1.5 to 2.5 in. H_2O	1.5 to 2.5 in. H_2O
Efficiency	Equal/better than host burner	Fly ash carbon = 2.3-11.0%	Fly ash carbon = 1.9-8.5%

The combustion efficiency, indicated by fly ash carbon content, was slightly better for the DMBs at the field unit than in the LWS. This again is directly related to the furnace thermal environment. However, efficiency was dependent to a large extent on a uniform air distribution at WIPCO. For conditions with balanced air flows, combustion efficiency was comparable to that achieved by the original equipment Intervane burners. Maldistribution of air flow through the burners resulted in substantially decreased efficiency, indicated by high carbon content of the ash.

6.0 DMB APPLICATION CONSIDERATIONS

The Distributed Mixing Burner (DMB) concept can be applied to both existing and new utility boiler designs for the purpose of controlling NO_x emissions. The field evaluation of the DMB during this program has provided the information necessary to determine the applicability to both design situations. As with all new technologies, a number of concerns arise that must be addressed. This is certainly true for the DMB technology. Some of those concerns are unique to the retrofit situation while others are common to all boiler applications. The following Subsection 6.1 discusses the new boiler application while Subsection 6.2 addresses the retrofit case.

The retrofit costs of this technology are so site-specific that even a general projection of those costs would be misleading. The concerns outlined in Subsection 6.2 should be evaluated for each prospective site to ultimately determine the suitability of a DMB retrofit.

The cost differential associated with applying the DMB technology to new boiler designs, however, can be presented in a useful manner. Using a modern NSPS utility boiler design as the base case, cost implications of designing the same boiler with the DMB firing system can be estimated with reasonable accuracy. Those cost differentials should enable users, architect/engineers, and manufacturers to assess the relative benefits of the DMB technology.

6.1 Applicability of the DMB Concept to New Utility Boiler Designs

The application of the Distributed Mixing Burner concept to new boiler designs, the primary development goal of this program, is not nearly as complex as the retrofit situations. This subsection discusses the DMB application to new boilers with emphasis on the differences compared to a conventional NSPS boiler design. The following subsection details the study approach. The remainder of the subsections discuss the boiler design and operating changes and cost impacts.

6.1.1 Study Approach

The approach taken for assessing the applicability and associated costs of applying the DMB concept to new utility designs was to compare a DMB-equipped boiler to its conventional NSPS equivalent. The majority of NSPS boilers sold by domestic manufacturers range in size from 450 - 750 MW_e maximum continuous rated capacity. A conventional NSPS boiler equipped with commercially-available "low-NO_x" burners was selected as the "base" case. Using the DMB design criteria presented in Subsection 2.0, a DMB firing system was designed for the same boiler. The cost impacts of the DMB system were then estimated and reported on a cost differential basis from the conventional design.

The "base" NSPS boiler selected for comparison is a 625 MW_e, opposed-fired, natural circulation boiler presently in operation in the Northeastern United States. A sectional side view of the boiler is shown in Figure 6-1. It is capable of continuously producing 4,750,000 lb/hr of steam at 2620 psig and 1005°F.

The boiler is arranged with a water cooled dry-bottom furnace, superheater, reheater, economizer, and air preheater. The firing system is designed to meet an NO_x emission limit of 0.7 lb/10^6 Btu and includes 48 "low-NO_x burners" which are supplied with pulverized bituminous coal from six pulverizers. The firing arrangement includes three elevations of burners, eight burners wide, on both the front and rear walls of the furnace. Heated secondary air is distributed to the burners utilizing a compartmented windbox which provides each elevation of burners independent air flow measurement and control.

The cost impacts of applying the DMB firing system, described in Subsection 6.1.2, are evaluated as a percent change from the base cost and are summarized in Subsection 6.1.6. The impact of the DMB design parameters on furnace sizing is discussed in the following Subsection, 6.1.3. The most significant modifications as a result of the DMB application are to the

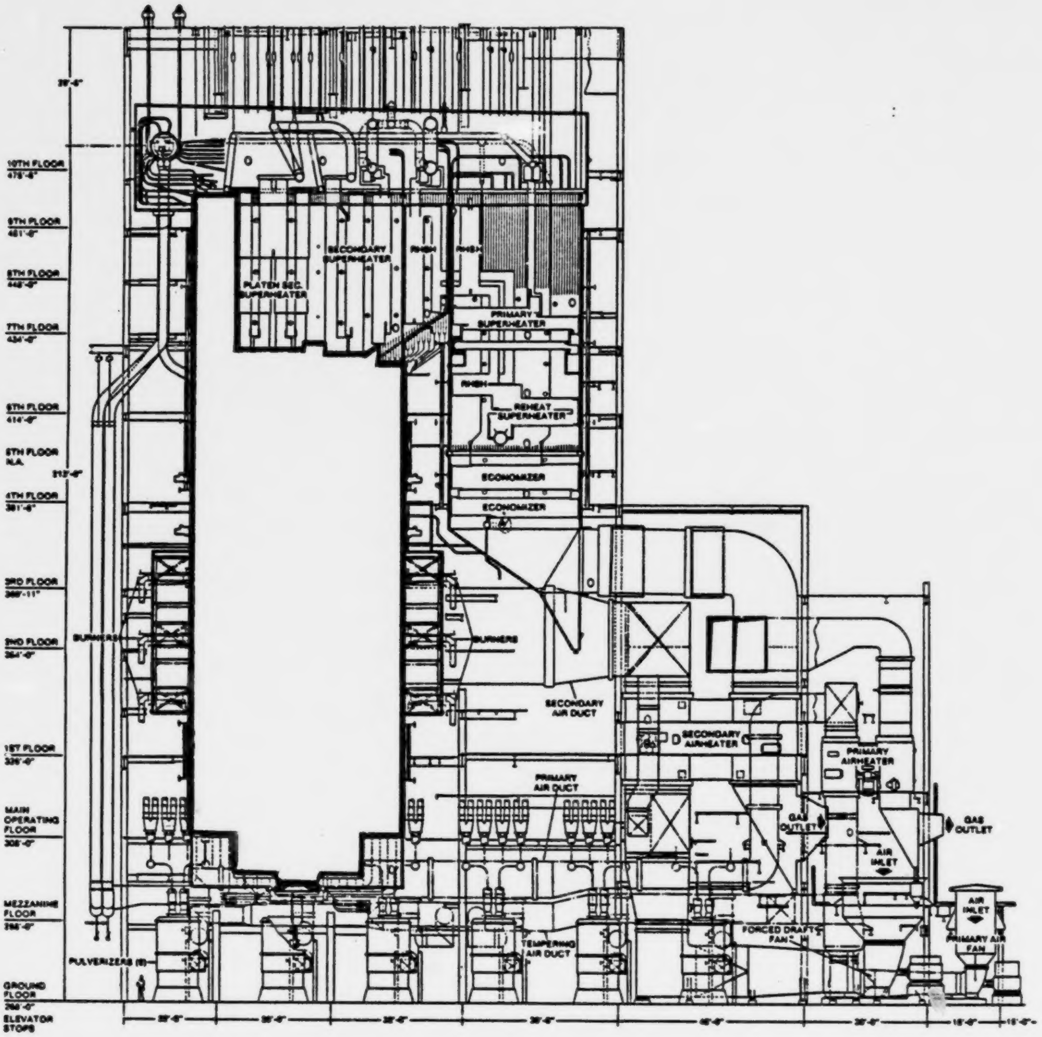

10TH FLOOR
9TH FLOOR
8TH FLOOR
7TH FLOOR
6TH FLOOR
5TH FLOOR N.A.
4TH FLOOR
3RD FLOOR
2ND FLOOR
1ST FLOOR
MAIN OPERATING FLOOR
MEZZANINE FLOOR
GROUND FLOOR
ELEVATOR STOPS
PLATEN SEC. SUPERHEATER
SECONDARY SUPERHEATER
RHSH
RHSH
PRIMARY SUPERHEATER
RHSH
REHEAT SUPERHEATER
ECONOMIZER
ECONOMIZER
BURNERS
BURNERS
SECONDARY AIR DUCT
SECONDARY AIRHEATER
PRIMARY AIRHEATER
PRIMARY AIR DUCT
GAS OUTLET
GAS OUTLET
AIR INLET
AIR INLET
PRIMARY AIR FAN
FORCED DRAFT FAN
TEMPERING AIR DUCT
PULVERIZERS (6)

Figure 6-1. Base 625 MW_e conventional boiler design.

firing wall panel construction and to the control system. These modifications are discussed in Subsections 6.1.4 and 6.1.5, respectively.

6.1.2 DMB Design

The conventional burners were designed to meet a fuel input capacity of 112 x 10^6 Btu/hr. As noted in the conventional boiler description, the unit was equipped with 48 burners. A significant adjustment that will have to be made when applying DMBs to new boilers is the reduction in the number of burners. By reducing the number of burners, and at the same time increasing the fuel input/burner, a boiler furnace sized in the conventional manner will not have to be changed for the DMB firing system. This is a much more cost effective approach than trying to maintain the same number of DMBs and changing the furnace dimensions to accommodate them. Additional space between burner throats is required by the DMB design to enable the tertiary ports to be located a sufficient distance from each throat to achieve reasonable NO_x emission reductions. Subsections 6.1.3 and 6.1.4 will discuss the furnace size criteria and the burner arrangement in the firing walls in much more detail.

For the above reasons, the DMB design for the cost analysis includes only 36 burners with a capacity of 149 x 10^6 Btu/hr each. The pulverized coal output of each pulverizer is simply split into six rather than eight streams. The total fuel input to the boiler remains constant as no change in boiler efficiency is predicted as a result of the firing system change.

Figures 6-2 and 6-3 show artist views of the conventional low-NO_x burner and of the distributed mixing burner as they appear from inside the boiler furnace. Note that the burner internals are similar for this study, as though both burners were built by the same manufacturer.

The major windbox change required is also illustrated in Figure 6-3. That change is the addition of a partition that divides the combustion air flow between the burner components and the tertiary air ports. The vertical partition is similar in construction to the horizontal plates that separate

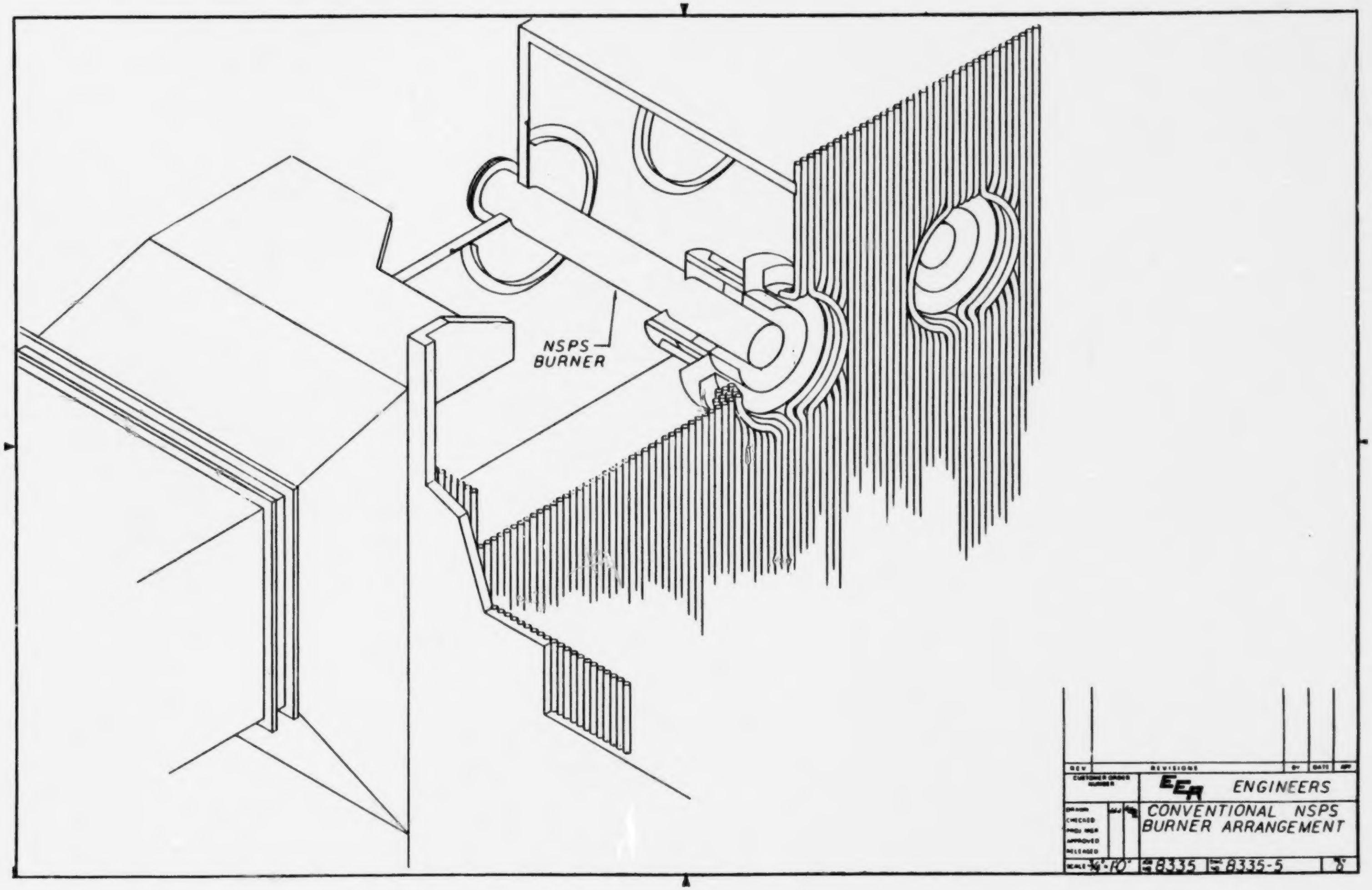

NSPS BURNER
REV
REVISIONS
DRAWN
CHECKED
APPROVED
RELEASED
SCALE
EER ENGINEERS
CONVENTIONAL NSPS BURNER ARRANGEMENT
8335
8335-5

Figure 6-2. Conventional NSPS burner arrangement.

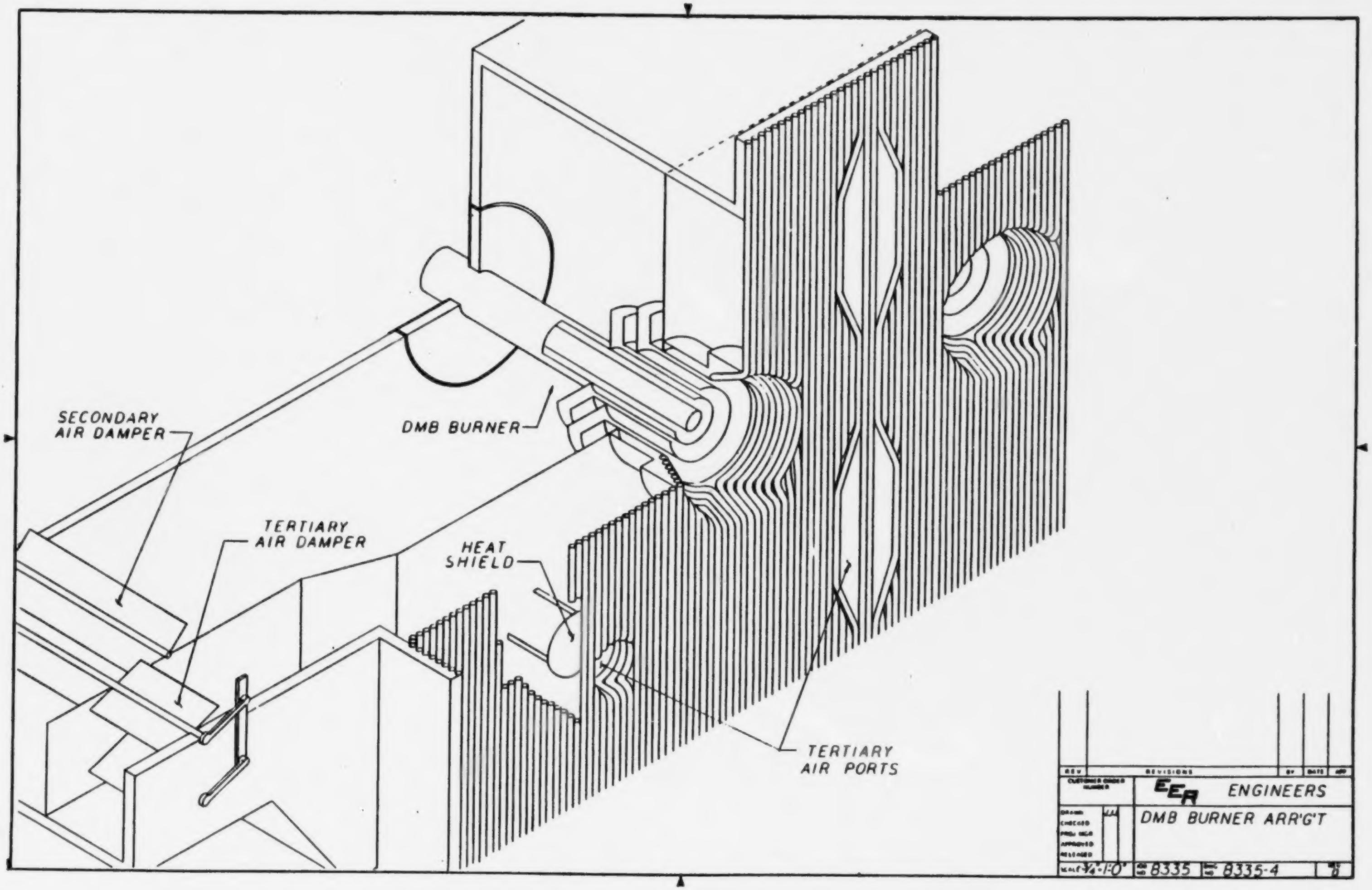

SECONDARY AIR DAMPER
TERTIARY AIR DAMPER
DMB BURNER
HEAT SHIELD
TERTIARY AIR PORTS
EER ENGINEERS
DMB BURNER ARR'G'T
SCALE ¼"=1'-0"
8335
8335-4

Figure 6-3. DMB burner arrangement.

the windbox into horizontal compartments. This compartmented windbox design allows independent air flow measurement and control for each elevation of burners. Since each elevation is also supplied fuel from an individual pulverizer with fuel flow measurement, the fuel/air ratio can be carefully controlled. The DMB firing system requires the addition of dampers to control the tertiary port air flow. Subsection 6.1.5, Operation and Control, will discuss the damper operation in detail.

All mechanical design constraints that apply to any equipment placed in the thermal environment of a utility boiler windbox would apply to the DMB. The maximum temperature of the burner materials, thermal stresses, differential thermal expansion, and protection from the furnace radiation are all important in the detailed design of the burner. For the purposes of this evaluation, there are no special design constraints associated with the DMB that are not presently applied to conventional firing systems.

The major design parameters, unique to the DMB, that are significantly different from conventional burners are those associated with the tertiary air ports. These ports, also illustrated in Figure 6-3, enable the burner to be operated at low burner zone stoichiometries to minimize NO_x emissions. For multiple burner applications, it is necessary to share tertiary port locations horizontally between burners. This is an important criteria to prevent furnace width from changing drastically and to reduce the number of openings in the furnace walls. These concepts will be discussed further in the following subsections. For the present, note that the ports are shared horizontally but not vertically. This maintains the independent firing control of each burner elevation/pulverizer "group".

The detailed design of the port opening is not critical either for the purposes of the economic evaluation or the performance of the DMB. Each boiler manufacturer will undoubtedly address the port design in a slightly different manner. A significant design consideration will be to minimize the radiant heat transfer to windbox components. The shared ports in particular are fairly large openings to that could expose large portions of windbox partitions and support members to direct flame radiation. This study assumes that protection will be afforded by a combination of the boiler wall tubes bent to form the opening, polished stainless steel "shine" plates to redirect much of the radiation back into the furnace, and constant secondary air flow through the port.

The port design illustrated in Figure 6-3 shows the shared tertiary ports were formed with two straight tubes through the center of the port. These tubes may tend to split the flow slightly and promote uniform tertiary air mixing between the burners.

The mechanical design details of internal burner components may vary significantly from manufacturer to manufacturer and still provide acceptable emissions reduction performance as long as the basic DMB tertiary port design criteria are met. Similar to the port design, those parameters can be met with a variety of different burner designs, materials of construction, fabrication techniques, etc. Each manufacturer can develop the specific detailed mechanical design with which he is most comfortable. The cost study assumed that the burner internals for a DMB will cost the same as the internals of a conventional low-NO_x burner of equivalent throat size.

The various design approaches for burner internal parts will result in operational characteristics varying from burner to burner. Flame shape, stability, turndown capability, and pressure drop will all be affected by each manufacturer's specific design.

6.1.3 Furnace Size

Boiler furnace sizing is primarily a function of coal quality and the past experience of the boiler designer with the design fuel. Two parameters used for describing furnace size are the Plan Area Heat Release Rate (PAHRR) and the Furnace Liberation Rate (FLR). Both parameters are used to define the early conceptual design of a boiler furnace. The exact size is finally determined by heat transfer calculations and certain manufacturing constraints. Both parameters, as well as the Burner Zone Liberation Rate (BZLR) discussed earlier, are widely used as a means of relating the combustion and emissions performance of one boiler to another. The BZLR parameter was developed to relate NO_x emissions performance to a parameter that was proportional to the flame zone bulk temperature. It is used primarily to determine burner spacing, and therefore burner zone height, in the furnace. All three parameters are used iteratively until an optimum furnace size is developed that combines satisfactory performance with minimum material, fabrication, erection, and operating costs.

The base boiler selected for this study was designed for a severe slagging coal and, consequently, has a fairly large furnace volume to provide lower flue gas temperatures entering the convective heat transfer surfaces of the boiler. The lower gas temperatures discourage the formation of troublesome ash deposits that are anticipated from the severe slagging classification of the design coal. The PAHRR and FLR parameters usually decrease with increasing furnace size and are relatively low for the base boiler. It is important to understand that, while the base boiler selected may not be perfectly representative of the existing population, it is quite representative of the boilers which will be designed and put into service over the next few decades. The trend toward furnace designs with lower PAHRR and FLR considerations over the past 15 years should continue into the foreseeable future. This is largely due to the lower quality coal sources that are being exploited and which will become the dominant sources of supply for new steam generation capacity.

Another criteria for furnace sizing that normally only applies to smaller (<150 MW_e) boilers is that of burner flame length. Particularly with single wall fired designs, the minimum furnace depth must be slightly longer than the burner flame length. Most conventional low-NO_x burner designs with capacities greater than 100 x 10^6 Btu/hr require a furnace depth of at least 25 feet. The unique fuel/air mixing characteristics of the DMB will require, in most cases for optimum emissions reduction, at least as much furnace depth to minimize rear furnace wall flame impingement. If maximum NO_x emissions reduction is not necessary, the DMB flame length can be reduced to suit a particular furnace depth constraint. Flame impingement must be avoided due to the probability of the tube overheating, ash deposition, and increased carbon loss which usually occur as a result.

The Plan Area Heat Release Rate is calculated by dividing the heat input of the furnace at maximum continuous rated capacity by the furnace plan cross-sectional area. That plan area is usually based on the area of a horizontal plane through the burner zone. For the base boiler design, the furnace dimensions at the burner zone are 73 ft. x 51 ft. or 3723 sq ft. and the total heat input is approximately 5376 x 10^6 Btu/hr. The PAHHR is therefore 1.44 x 10^6 Btu/hr-ft^2. The majority of NSPS boilers are designed with a PAHHR in the range of 1.4 to 2.0 x 10^6 Btu/hr-ft^2. As the slagging tendencies of the design fuel become more severe, the furnace PAHHR will tend to move toward the lower end of the existing range. As fuel quality declines in the future, the "representative" range for PAHHR will also decline.

In a similar manner, the Furnace Liberation Rate decreases as the coal quality, and therefore, furnace size increases. For the conventional boiler design selected, the furnace volume is approximately 490,000 ft^3. The FLR is calculated by dividing the heat input, 5376 x 10^6 Btu/hr, by the furnace volume. The base boiler FLR is approximately 10,970 Btu/hr-ft^3 which, again, is toward the lower end of the design range of 10,000 - 30,000 Btu/hr-ft^3. In similar fashion to the PAHHR, as the slagging tendencies of the design fuel become more severe, the FLR will tend to move toward the lower end of the existing range. As fuel quality declines in the future, the "representative" range for FLR will also decline.

The minimum space required between a burner throat and a furnace sidewall is also a function of burner performance and coal quality. Slagging can become a serious problem on sidewalls that are too close to a burner which, in turn, can lead to tube failures. Mechanical connections to the boiler corners, limiting the heat flux to the sidewall tubes, and other factors all enter into the determination of the minimum burner/sidewall spacing criteria. Conventional boiler design philosophy has normally set the spacing restriction between 5 and 15 feet. Figure 6-4 illustrates a recommended relation between burner heat input and sidewall spacing. The

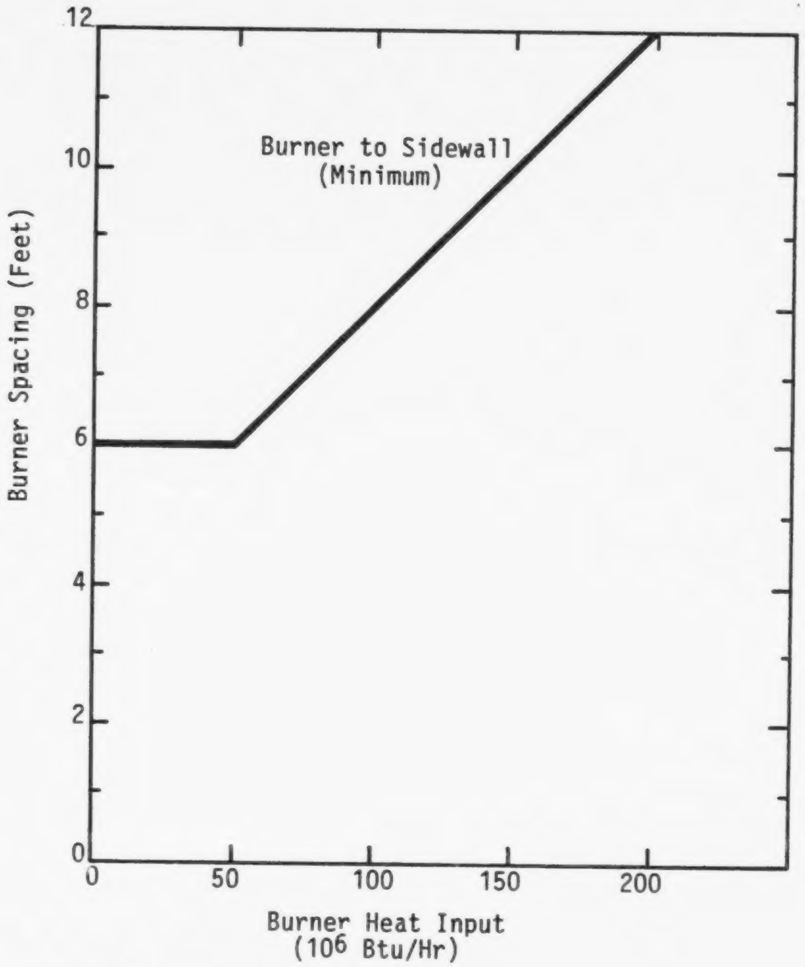


Figure 6-4. DMB boiler burner to sidewall spacing.

design of the DMB should not impact any of these spacing criteria in a negative manner. Actually, since the tertiary air ports are adjacent to the sidewalls, many of the gas-side problems normally encountered should be minimized. A 10 ft. minimum sidewall spacing was assumed for the DMB in the new boiler application.

The application of the DMB to new boiler designs should not significantly impact conventional furnace sizing procedures. In the majority of new boilers designed in the future, conventional furnace sizing criteria, based on predicted coal quality effects, should be applied to boilers equipped with DMB firing systems. Some minor modifications to the furnace size may be appropriate based on the burner/tertiary port arrangement on each firing wall. Figure 6-5 can be used as a guide for selecting the size and number of DMBs for each firing wall. The figure assumes that the DMB design parameters are followed and that the tertiary air ports are shared horizontally between burners.

6.1.4 Firing Wall Arrangement

The design of the firing wall has been the object of much concern and attention during the development of the DMB concept. The necessity of the tertiary air ports, requiring a substantial increase in the number of openings in the firing walls, has always been considered detrimental to the concept application. While the DMB retrofit at WIPCO's Pearl Station seemed to support that concern, the new boiler application does not. The extreme number of constraints imposed by the retrofit situation do not apply in the new boiler design case.

The firing wall arrangement is determined by DMB throat size, tertiary port design, burner spacing, and spacing between the furnace side walls and adjacent burners. The design approach, and possible alternatives, of each are addressed in further detail below before presenting the arrangement selected for the DMB cost analysis. Comments referring to "pre-NSPS" and "NSPS" burners are intended to represent generic burner design practices used

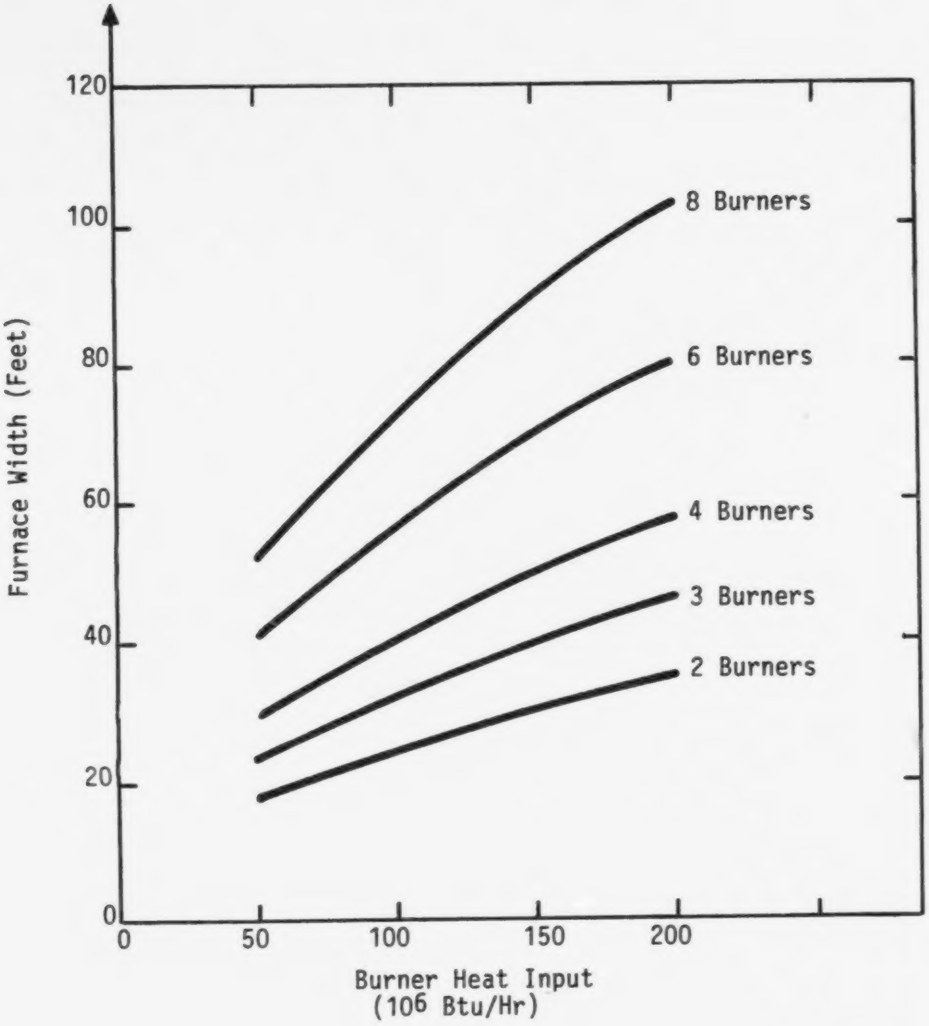


Figure 6-5. DMB boiler furnace width.

by the burner supply industry before and after promulgation of the New Source Performance Standards in 1972.

Throat Design

The throat opening diameter, calculated per the DMB design criteria, varies with the burner heat input. Figure 6-6 illustrates the relative throat diameters of typical pre-NSPS, conventional NSPS, and DMB burner designs as a function of heat input. Even though the DMB throat velocity is lower than either of the other burner types, the reduced secondary air flow required to maintain a 70 percent burner zone stoichiometry results in a smaller throat opening. These dimensions are approximate. The specific burner designs employed by some burner manufacturers such as the core air passage in Foster Wheeler burners may increase throat diameter for the same primary and secondary velocities.

Tertiary Port Design

The design of the tertiary air ports includes the port size, shape, and radial distance from the burner throat. While the port flow area and radial distance are defined by the DMB design parameters, the final port design can vary widely depending on the strategy used for determining the total number of ports and for controlling the air flow to the ports.

Ideally, the port design is a simple circular wall opening with four individual ports per burner. Practically, however, the expense incurred by accommodating that approach is prohibitive. The large number of furnace wall tubes that must be bent to form the ports and the additional furnace width required makes this approach very unattractive. To minimize the furnace width impact of the DMB application, it is desirable to share ports horizontally between burners. To minimize the number of tubes bent, the port shape should be lengthened parallel to the orientation of the furnace wall tubes. In most domestic applications where the wall tubes are oriented vertically, the "ideal" round port should become rectangular in shape with the longer dimension of the rectangle oriented vertically also.

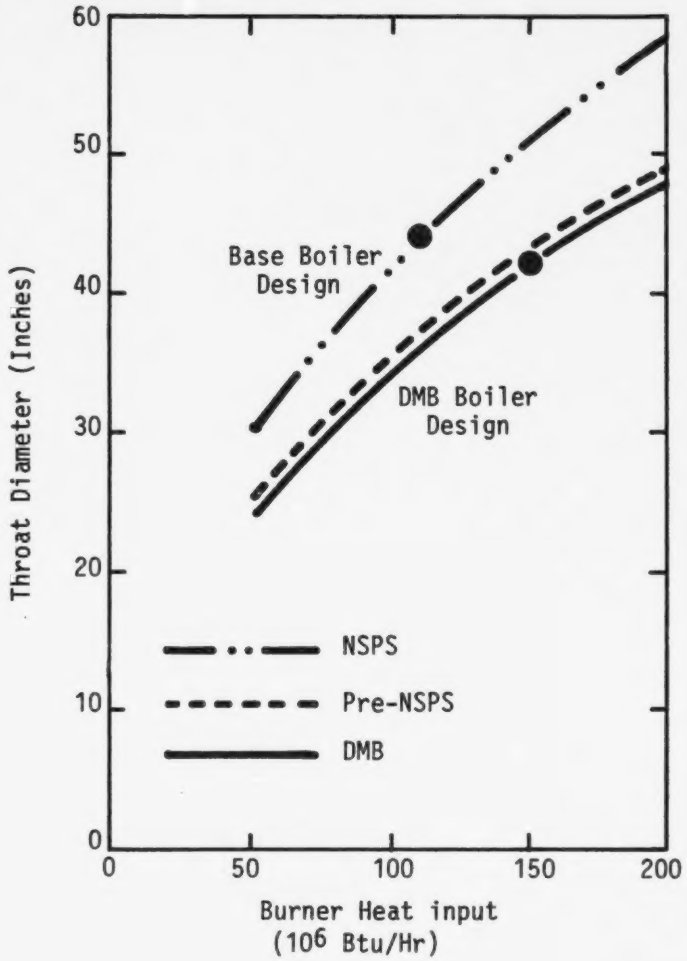


Figure 6-6. Relative burner throat diameters.

Individual ports for every burner requires the maximum number of port openings in the firing wall. The minimum number of openings are required if ports are "shared" both vertically and horizontally (similar to the WIPCO arrangement). Shared ports refer to ports designed to provide tertiary air to more than one burner. Depending on the location of the ports with respect to the burner throats, and whether it is shared in more than one direction, a port could be shared by up to four burners. However, to minimize burner balancing problems, port sharing should be minimized.

In order to minimize the number of wall tubes that must be bent to form the tertiary port openings, sharing ports horizontally is highly desirable. Since the load-bearing capability of a tube is reduced once it is bent, having multiple ports in the vertical direction can be tolerated. In addition, since virtually all firing control systems are based on horizontal groups of burners (firing elevations), horizontally shared port air flows can be easily controlled in conjunction with their respective burners (discussed further in Subsection 6.1.5). Based on these two important considerations, the DMB firing wall arrangement utilized for the economic analysis includes horizontally shared tertiary air ports.

Burner Spacing

The space between burners adjacent to one another in the firing wall is largely determined by the tertiary port location criteria (horizontally) and by burner zone liberation rate (BZLR) furnace criteria (vertically). Figure 6-7 illustrates the horizontal burner spacing required (throat centerline to centerline) for burners as a function of heat input. The correlation for both individual and horizontally shared tertiary air ports is shown. The minimum vertical burner spacing will be the same unless BZLR criteria require wider spacing which results in increasing the burner zone volume and therefore reducing the BZLR.

Figures 6-8 and 6-9 illustrate the burner throat and tertiary air port openings on one firing wall from both the conventional low-NO_x boiler design and the DMB design, respectively. Both firing systems utilize exactly the

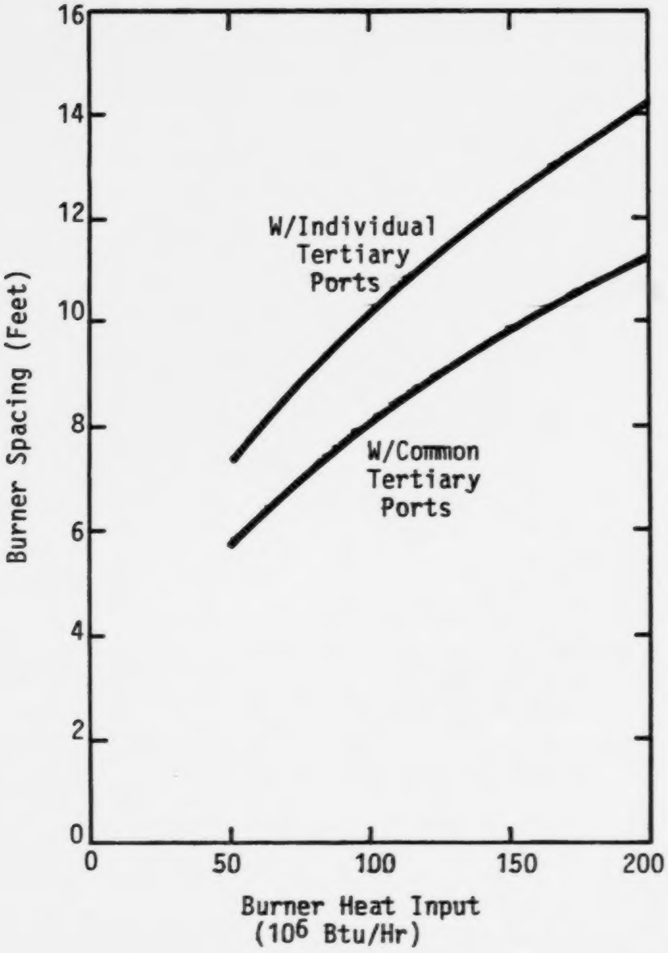


Figure 6-7. DMB boiler burner-to-burner spacing.

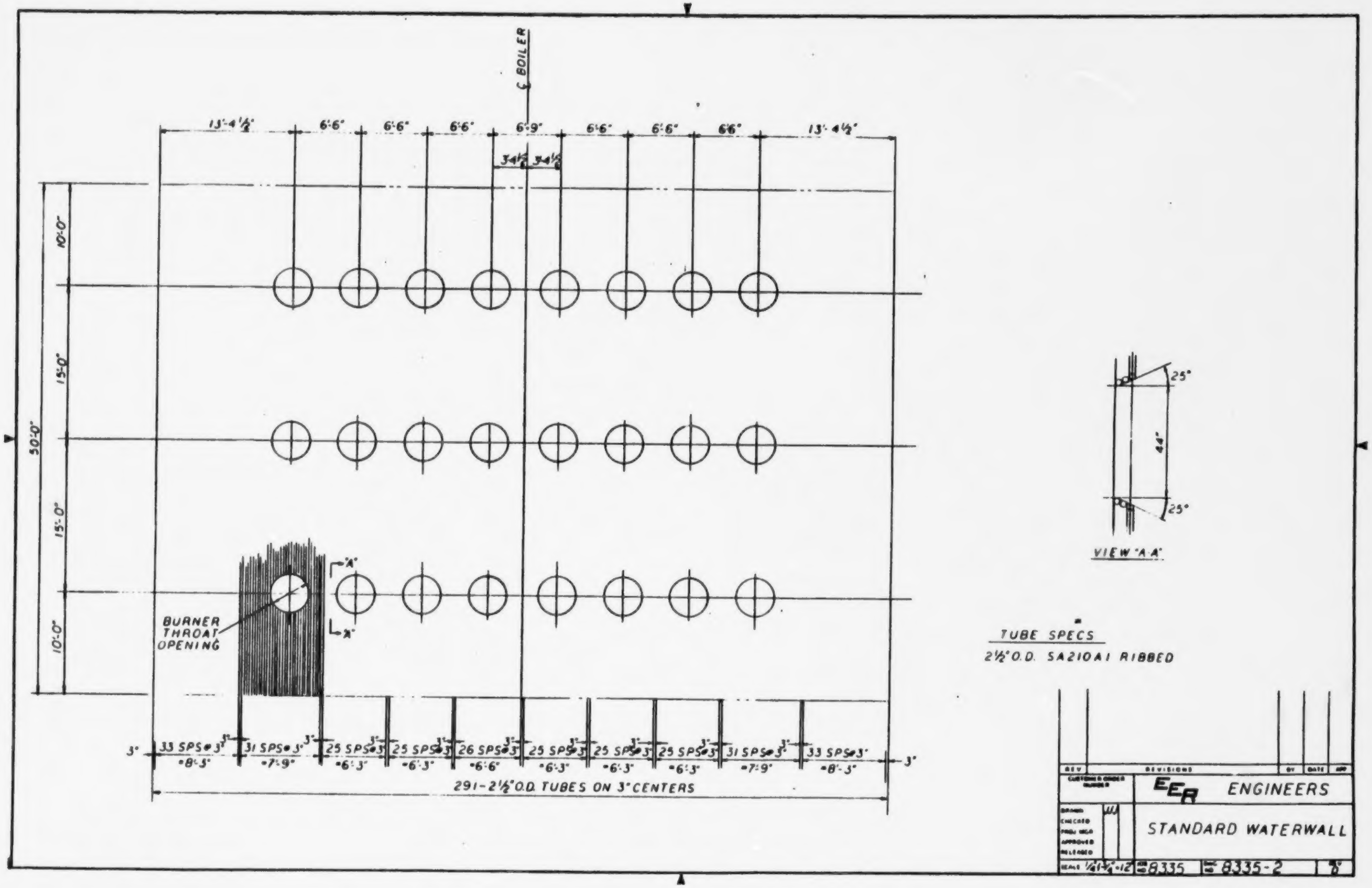

℄ BOILER
13'-4½"
6'6"
6'6"
6'6"
6'9"
6'6"
6'6"
6'6"
13'-4½"
3'4½"
3'4½"
10'-0"
15'-0"
15'-0"
10'-0"
50'-0"
"A"
"A"
BURNER THROAT OPENING
3"
33 SPS @ 3" =8'-3"
31 SPS @ 3" =7'-9"
25 SPS @ 3" =6'-3"
25 SPS @ 3" =6'-3"
26 SPS @ 3" =6'-6"
25 SPS @ 3" =6'-3"
25 SPS @ 3" =6'-3"
25 SPS @ 3" =6'-3"
31 SPS @ 3" =7'-9"
33 SPS @ 3" =8'-3"
3"
291-2½" O.D. TUBES ON 3" CENTERS
25°
44"
25°
VIEW "A-A"
TUBE SPECS
2½" O.D. SA210A1 RIBBED
REV
REVISIONS
BY
DATE
EER ENGINEERS
STANDARD WATERWALL
8335
8335-2

Figure 6-8. Conventional NSPS firing wall.

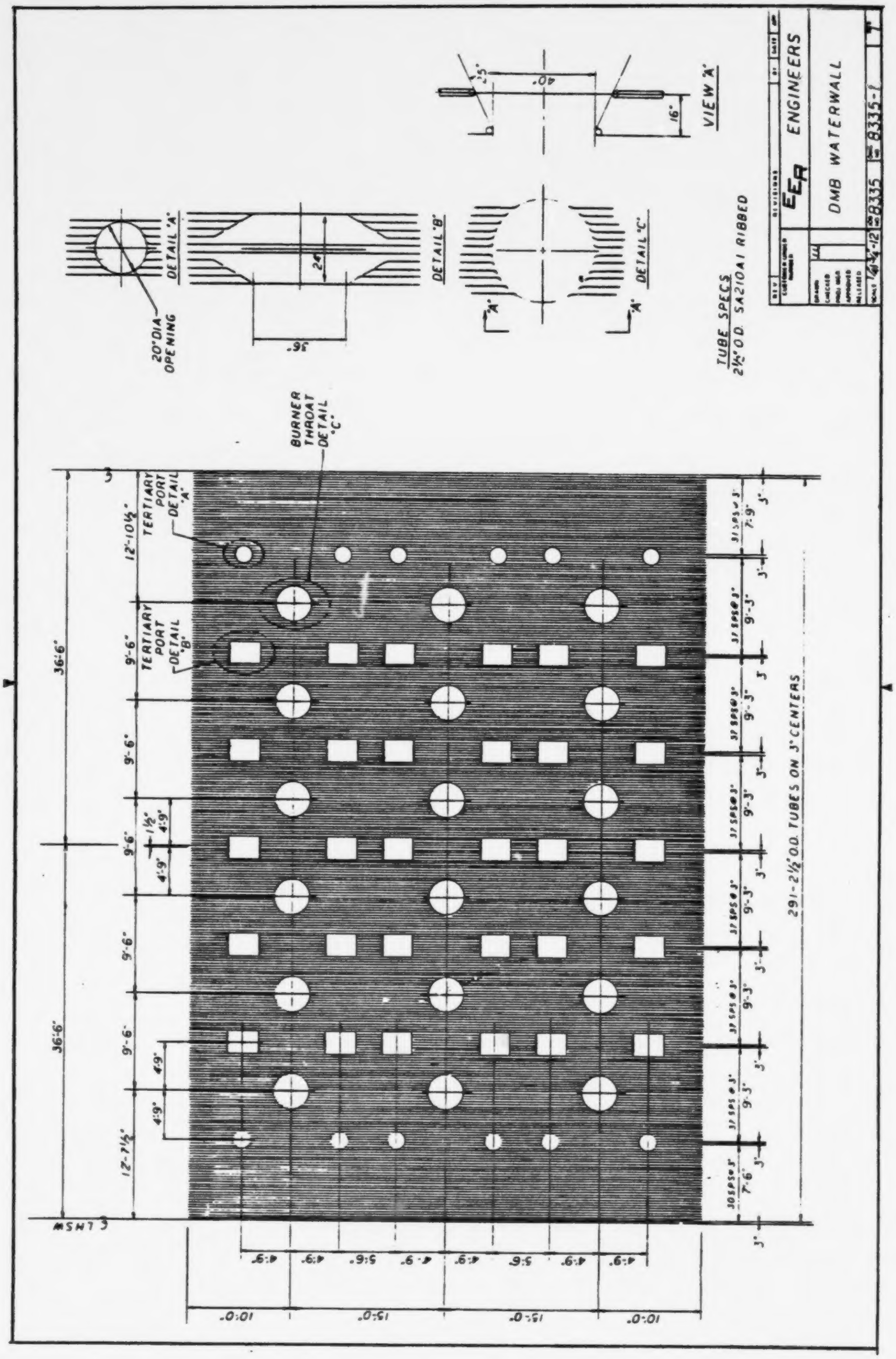

TERTIARY PORT DETAIL 'A'
BURNER THROAT DETAIL 'C'
TERTIARY PORT DETAIL 'B'
36'-6"
12'-10½"
9'-6"
12'-7½"
291-2½" O.D. TUBES ON 3" CENTERS
10'-0"
15'-0"
20" DIA OPENING
DETAIL 'A'
DETAIL 'B'
DETAIL 'C'
VIEW 'X'
TUBE SPECS
2½" O.D. SA210A1 RIBBED
ENGINEERS
DMB WATERWALL
8335-1

Figure 6-9. DMB firing wall.

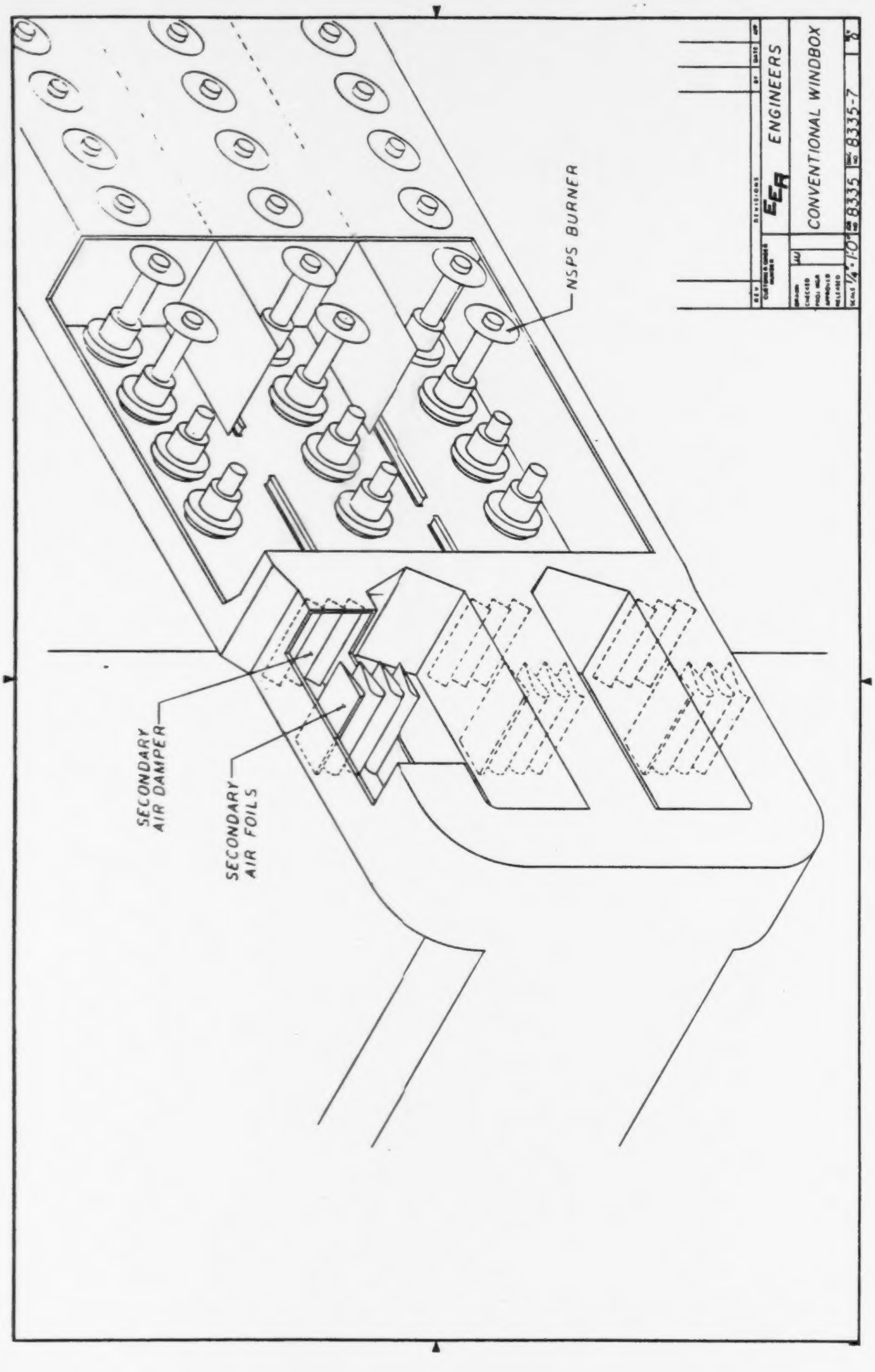
same furnace size in all dimensions. This is accomplished, while still meeting the DMB design criteria by reducing the number of burners on each wall and by sharing tertiary air ports horizontally between burners. The cost impact of the change in firing wall design is discussed in Subsection 6.1.6.

Firing wall panel construction would not change from the conventional panels. Both panels would be of membrane wall construction utilizing 2-1/2 in. O.D. tubes spaced on 3 in. centerlines with a small bar welded between them to form a flat wall section. This typical design provides a continuous wall surface of high strength and gas tight construction. The panels are fabricated to dimensional limits of approximately 10 ft. x 50 ft. and are welded together at the construction site to form the furnace enclosure.

There are no changes to any of the conventional fabrication, shipping, or erection procedures as a result of the DMB application. However, there is a slight decrease in the erection effort required for the DMB application as each firing wall has only eight panels as opposed to ten on the conventional design. This will impact the field erection costs by reducing the number of crane "lifts" to complete the furnace wall and also by reducing the number of longitudinal welds that are made to connect the panels.

Figures 6-10 and 6-11 shows the secondary air duct and windbox arrangement for the conventional and DMB boiler designs, respectively. Note, for the DMB application, the additional air flow control dampers (one at each end of every compartment) and measuring air foils that provide control of the air flow through the tertiary air ports. Each horizontal windbox compartment must be further divided into two "sub-compartments" by the vertical partition plate that divides the windbox into two smaller windboxes, one for the burner air flow and the second for the tertiary port air flow. These design changes will be discussed in more detail in the following section.

It is important to determine the firing wall arrangement early in the new boiler conceptual design process as the balance of the windbox


NSPS BURNER
SECONDARY AIR DAMPER
SECONDARY AIR FOILS
EER ENGINEERS
CONVENTIONAL WINDBOX
1/4" = 1'-0"
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8335-7

Figure 6-10. Conventional NSPS duct/windbox arrangement.

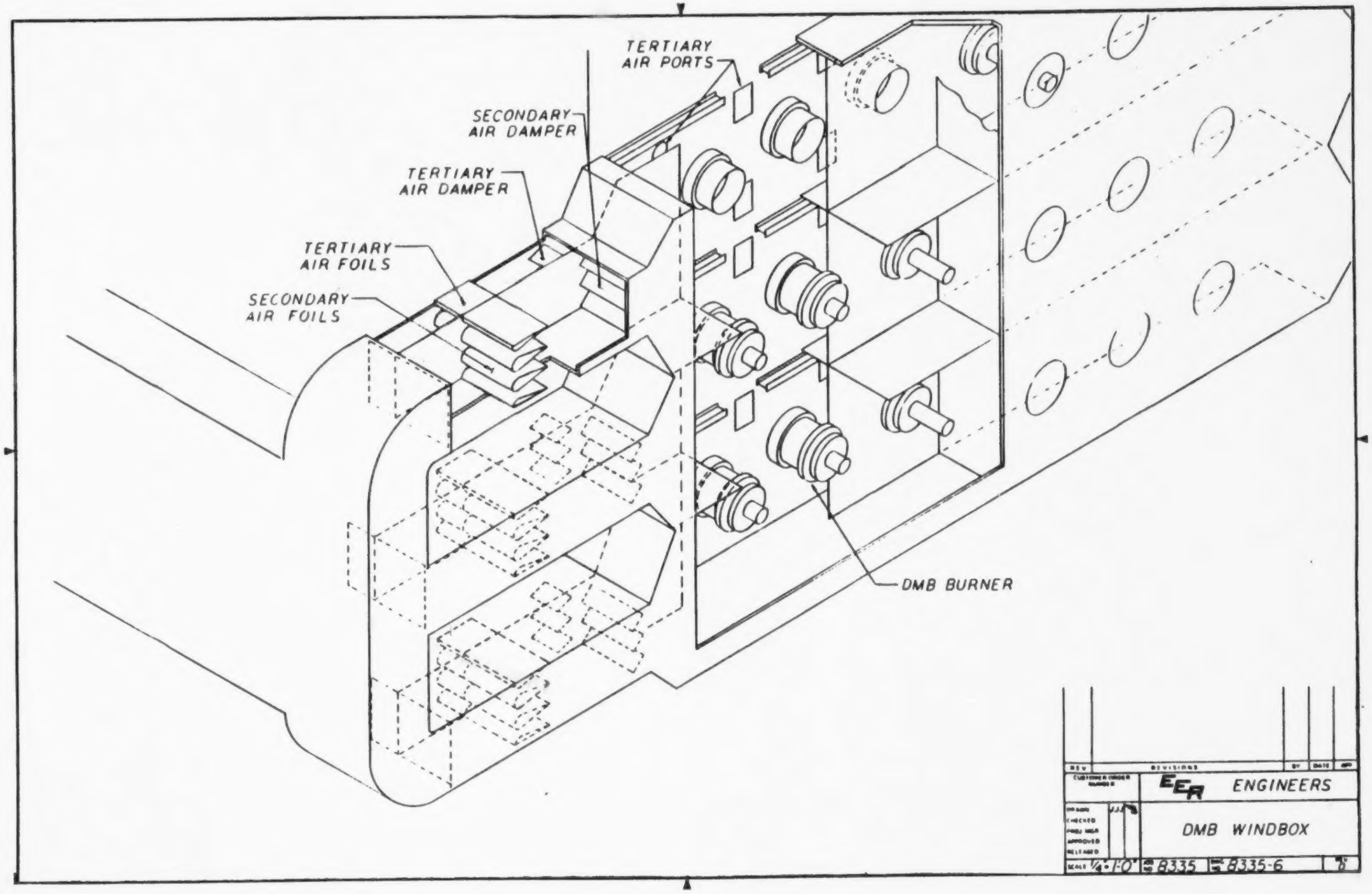

TERTIARY AIR PORTS
SECONDARY AIR DAMPER
TERTIARY AIR DAMPER
TERTIARY AIR FOILS
SECONDARY AIR FOILS
DMB BURNER
EER ENGINEERS
DMB WINDBOX
1/4"=1'-0"
8335
8335-6

Figure 6-11. DMB duct/windbox arrangement.

arrangement, including the location of structural members in the windbox, is highly dependent on the burner throat and tertiary air port locations.

It does not appear that the application of the DMB to new boilers will impact the structural design to any significant extent. Although the windbox weight will increase somewhat due to the modifications necessary to measure and control both the burner and tertiary air flows, the weight of the burners will decrease. The results are an insignificant net weight change.

By utilizing a reduced number of burners and horizontally shared, rectangular port openings, the number of tubes in each firing wall requiring bending increases by only eight tubes. The conventional design requires 120 of the 291 wall tubes to be bent. The DMB design requires bending 128 tubes which will theoretically increase the loading on the remaining straight tubes by less than 5 percent. This modest increase will not require any structural modifications.

6.1.5 Operation and Control

The operation and control will differ from that of the conventional boiler only in that, above "control" load (65 percent), the total secondary air to the burners may be split between the burner flow and the tertiary air flow. Except for the added capability to measure and control that additional secondary combustion air stream, the boiler control system is unaffected by the DMB firing system arrangement. All turbine/generator, boiler, firing system, and flame safety systems are identical to those on a conventional boiler equipped with a typical NSPS firing system.

The DMB control philosophy is that, below control load, NO_x emissions are at acceptable levels without utilizing the staged combustion capability of the DMB design. Burner zone stoichiometries remain above 100 percent and the operating characteristics are much like those of a conventional NSPS burner. This approach will provide enhanced carbon burnout, flame stability, and burner turndown for better low load operation.

As boiler load increases above control load, the additional combustion air required will be admitted into the furnace through the tertiary air ports. At full load, enough air will be diverted through the ports to achieve the design burner zone stoichiometry of 70 percent resulting in minimum NO_x emissions. Figures 6-12 and 6-13 illustrate the air flow control function and burner zone stoichiometry relationship.

An alternate control approach could be used to reduce NO_x emissions further at low load. The burner zone stoichiometry could be maintained at the design point as load is reduced by reducing the secondary and tertiary air flows in parallel. This approach could be used down to the limit of burner turndown. Then one or more pulverizers could be removed from service for operation at lower load.

The measurement and control of the tertiary air port flow is a most important factor in the performance of the DMB firing system. The DMB-fired boiler designed for economic analysis utilizes a separate windbox sub-compartment for separating the burner and tertiary air flows. The air flow measurement and control can then be accomplished at only two points - each end of the compartment. This method is much more cost effective than an arrangement such as that utilized at the WIPCO demonstration where ports were controlled individually. With the windbox compartments arranged such that each compartment supplies only those ports associated with one pulverizer burner group, the group burner zone stoichiometry can be accurately controlled. On large boilers fired with a number of pulverizers, it is desirable to provide some form of tertiary port flow control in order to minimize the flow when pulverizers and burners are not being used. This assures low load boiler operation at acceptable excess air levels. In addition, as the DMB is operated at lower loads, the tertiary port flow can be held at the minimum flow required for cooling (approximately 10 percent design flow). This results in the DMBs operating at higher low load windbox-to-furnace air pressure differentials which results in better efficiency through reduced carbon loss and minimum excess air.

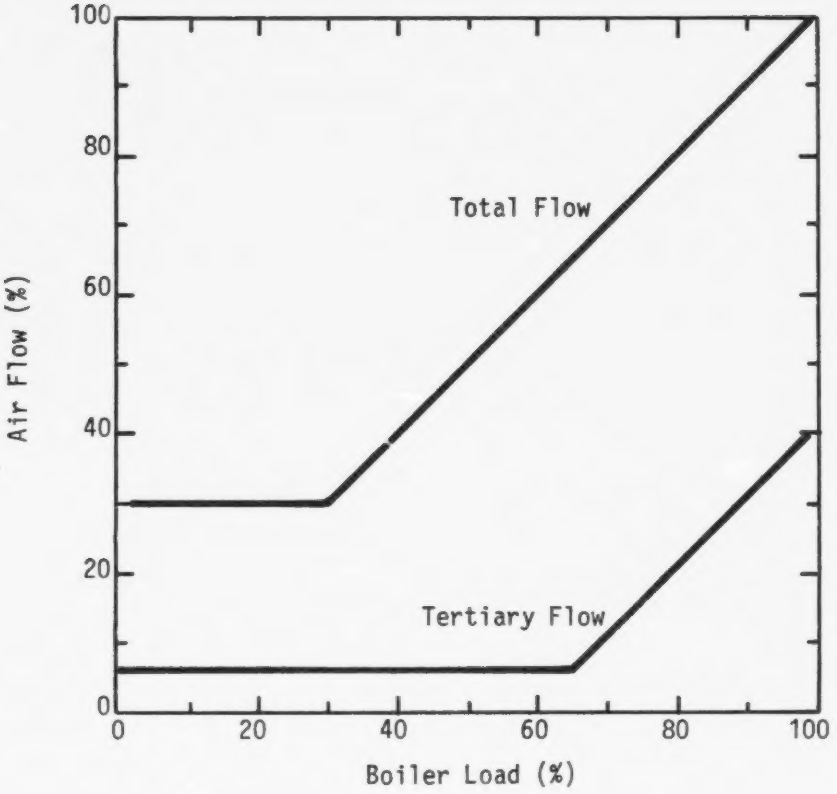


Figure 6-12. DMB boiler air flow.

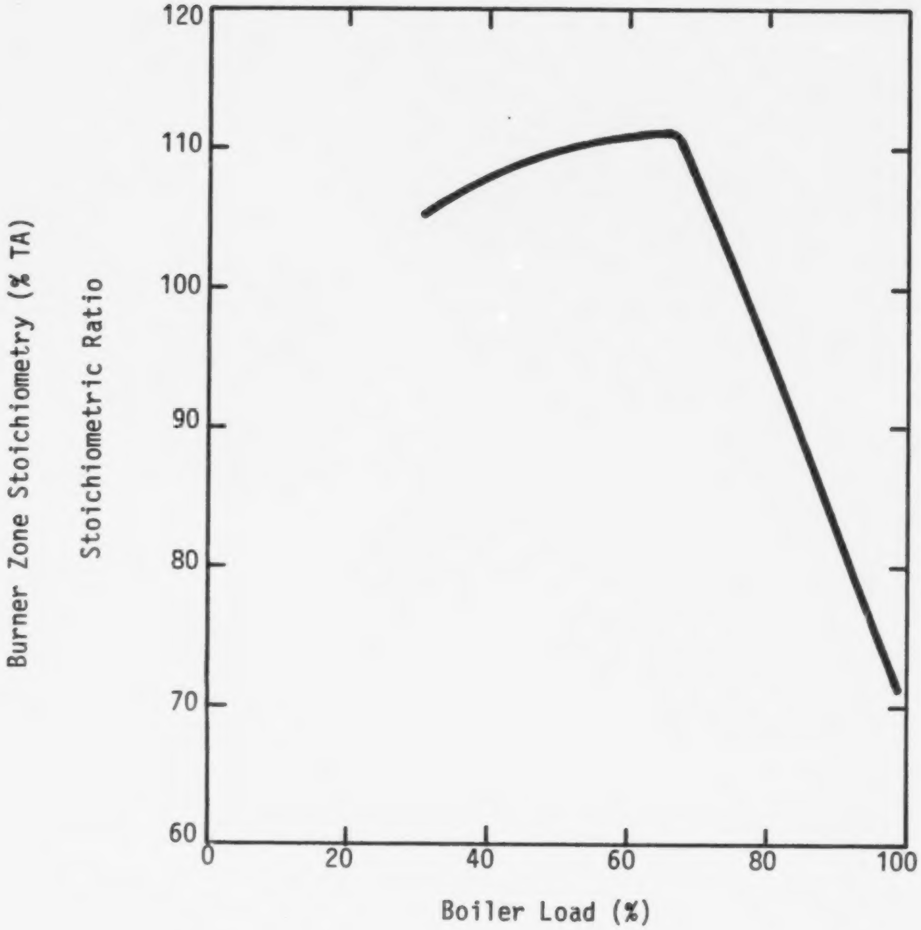


Figure 6-13. DMB boiler burner stoichiometry.

Historically, accurate measurements of air flow in large boiler ducts has been an area of concern for boiler designers and operators. There are occasional lengths of ductwork where the application of a venturi-type flow meter can be applied for measuring combustion air flows. Insufficient lengths of straight duct, varying air temperatures (up to 700°F) and pressure, and entrained fly ash particulates present a harsh environment for flow measurement instrumentation. Two alternatives available for flows in large ducts with straight runs too short for the application of a venturi metering section are air foils and honeycomb flow straightening sections followed closely by pitot static probe grids. The air foil flow meter is the most widely used flow metering technique in the utility industry. Figure 6-10 showed the application of air foils in the secondary air feeder ducts to each of the windbox compartments. Figure 6-11 illustrated the DMB modification required to add a second pair of air foils and dampers to measure and control the tertiary port flow.

Upon initial start-up, flow could be balanced to each port in the compartment using cold air. Once balanced, there would be no further monitoring of flow on an individual port basis. An alternative would be to add a control device at each port, adjustable during boiler operation, to obtain equal pressure drop, and therefore equal flow, across all ports. This was not included in the economic evaluation of the DMB application. Because the tertiary port flow is measured on an individual pulverizer basis, the desired stoichiometry will be maintained for each burner group even though there will be minor variations in individual burner stoichiometries due to occasional maldistributions of coal and air flows to individual burners within the group.

Figure 6-14 illustrates the only portion of the boiler controls affected by the DMB operating requirements, the fuel and air flow control subsystem. The schematic illustrates the data inputs to the system (circles) and the control signal outputs (hexagons). The addition of the DMB tertiary port air flow requires one additional control input, tertiary port flow, which is provided by the ΔP transmitter attached to each air foil flow meter. The system provides one additional output signal which operates the tertiary port

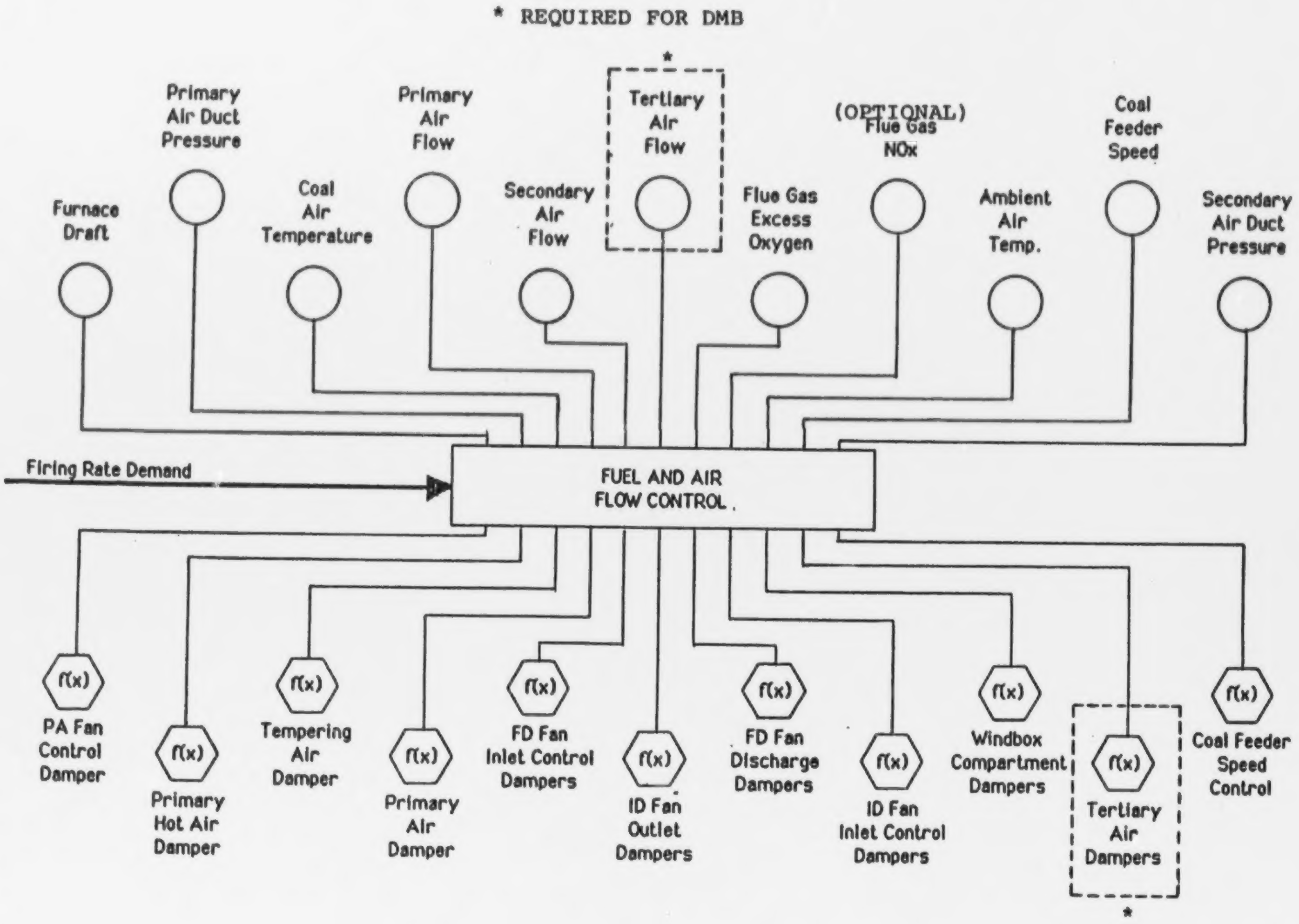

* REQUIRED FOR DMB
Furnace Draft
Primary Air Duct Pressure
Coal Air Temperature
Primary Air Flow
Secondary Air Flow
* Tertiary Air Flow
Flue Gas Excess Oxygen
(OPTIONAL) Flue Gas NOx
Ambient Air Temp.
Coal Feeder Speed
Secondary Air Duct Pressure
Firing Rate Demand
FUEL AND AIR FLOW CONTROL
f(x)
PA Fan Control Damper
Primary Hot Air Damper
Tempering Air Damper
Primary Air Damper
FD Fan Inlet Control Dampers
ID Fan Outlet Dampers
FD Fan Discharge Dampers
ID Fan Inlet Control Dampers
Windbox Compartment Dampers
Tertiary Air Dampers *
Coal Feeder Speed Control

Figure 6-14. Control subsystem schematic.

damper drives as a function of load. An additional level of control could be incorporated by adding a flue gas NO_x concentration input signal. That signal could be used to further adjust the tertiary port flow and therefore provide a control loop that would continually adjust burner zone stoichiometry to achieve a desired NO_x emission level.

Figure 6-15 illustrates the air flow streams on the DMB boiler design and the important control points throughout the system.

6.1.6 Estimated Cost Impacts

The cost impacts estimated in this section are intended as a general indication of the changes that must be considered when applying a DMB firing system to new boiler designs; the costs shown are only approximate. Actual costs will be dependent on the burner design approach utilized by each manufacturer and on numerous factors which are influenced by individual boiler designs.

In order to fairly evaluate the relative cost of DMB applications, two "base" NSPS boiler designs must be considered which encompass almost all wall-fired domestic utility boilers presently offered. Case A is typical of an NSPS design that utilizes a relatively large number of burners (48 @ 112 x 10^6 Btu/hr) situated in a horizontally compartmented windbox (similar to the design shown in Figure 6-10). Case B is typical of an NSPS design that utilizes a smaller number of higher capacity burners (30 @ 180 x 10^6 Btu/hr) situated in a non-compartmented windbox. For the purpose of this study, it is assumed that the furnace dimensions are approximately the same for both designs assuming identical steam generation capacities. The Case A cost analysis is based on the assumption that the number of burners will be reduced to 36 while Case B requires no change in the burner quantity.

Each cost itemized is expressed as a differential cost that is based on comparing the equivalent engineering, fabrication, and material scope of a conventional NSPS boiler design with the DMB-fired boiler design. Each is

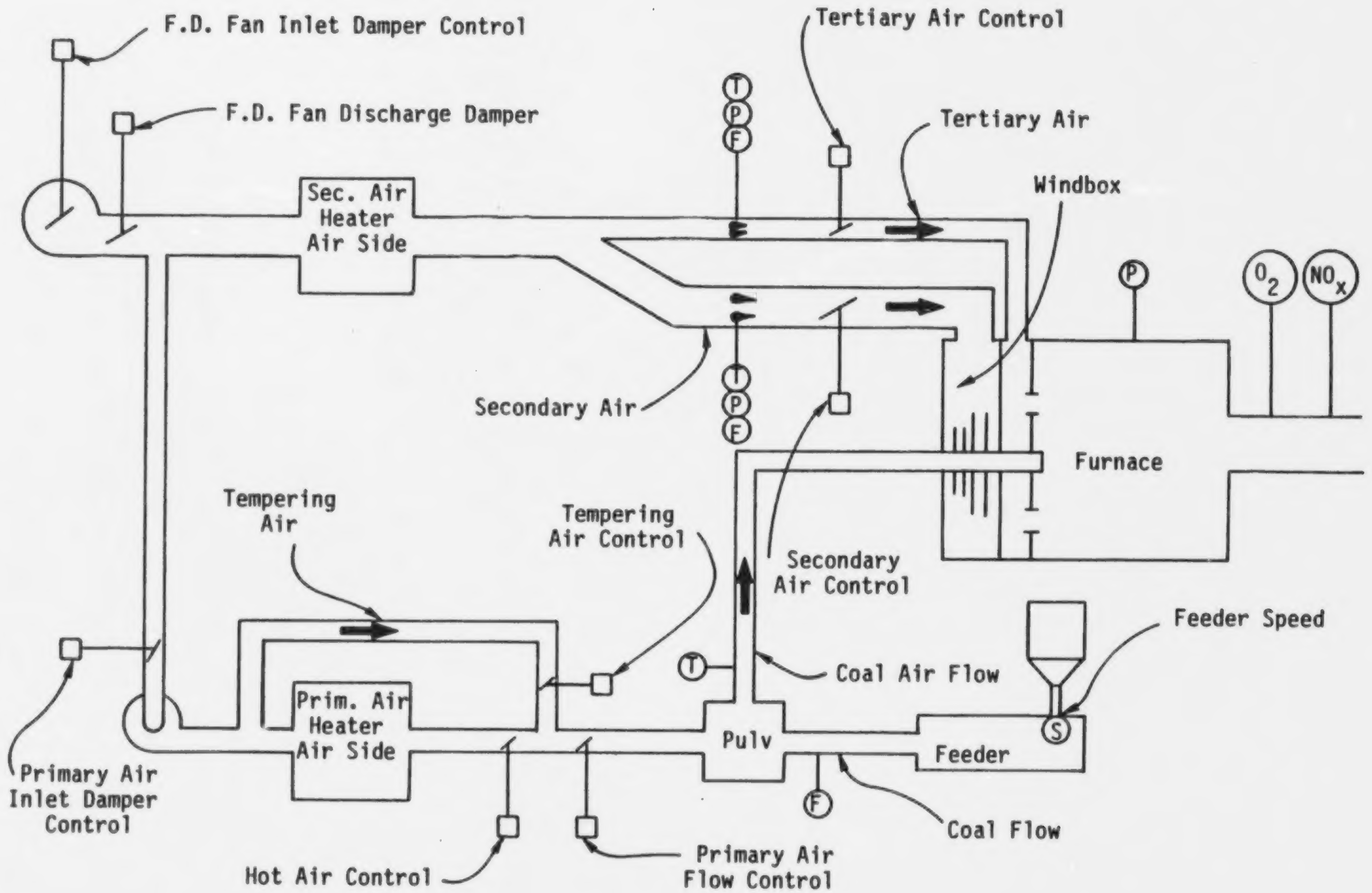

F.D. Fan Inlet Damper Control
F.D. Fan Discharge Damper
Sec. Air Heater Air Side
T
P
F
Tertiary Air Control
Tertiary Air
Windbox
P
O2
NOx
Secondary Air
T
P
F
Furnace
Tempering Air
Tempering Air Control
Secondary Air Control
Feeder Speed
T
Coal Air Flow
S
Prim. Air Heater Air Side
Pulv
Feeder
Primary Air Inlet Damper Control
F
Coal Flow
Hot Air Control
Primary Air Flow Control

Figure 6-15. Air flow - DMB unit.

discussed below followed by a brief discussion of the impact of the changes on the erection of the DMB boiler design.

To provide a point of reference for these costs, the conventional NSPS boiler design (625 MW_e) studied would cost approximately $55,000,000 (1986 dollars). Erection would be an additional $29,250,000. The material scope of supply would include the following:

Summary of Major Equipment

Furnace (Primary and Secondary)
Superheater and Attemperator
Reheater and Attemperator Internals
Economizer
Tubular Air Heater (Primary)
Regenertive Air Heater
Steam Coal Air Heater
Pulverizers and Drives
Coal Feeders and Drives
Raw Coal Piping
Burners
Burner Piping
Lighters
Brickwodk
Refractories
Insulation
Lagging
Thermocouples and Thermoproves
FD-ID Fans and Drives
Recirculated Gas Fans and Drives
Primary Air Fans and Drives
Television
Steam Temperature Control
Integrated Boiler - Turbine Generator Control
Burner Control

Flame Monitoring Equipment
Structural Steel, including Platform Support
Top Support Steel (Grid), including Platform Support
Support Rods and Hangers
Platforms, Grating and Stair Treads
Soot Blowers and Drives
Recirculated Gas Dust Collector

Table 6-1, Terminal Points, further defines the scope of equipment included in the study.

The cost impacts of the DMB application to the Case A new boiler design is summarized in Table 6-2 and the cost impacts of the DMB application to the Case B new boiler design is summarized in Table 6-3.

Burners

The cost of the DMB itself can be assumed to be the same as an NSPS burner requiring a similar throat size provided by the same manufacturer. For the purpose of this study, the conventional NSPS burner with a 44" throat was assumed to cost $18,600 and the 40" DMB $18,000. As is always the case with new product applications, some additional engineering will be required on the first boiler application. However, it is not anticipated to be a significant increase as each manufacturer is expected to utilize his standard burner components for the DMB design.

A net savings is realized by the DMB approach due to the slightly lower burner cost (slightly smaller burner size). In the Case A boiler design, a significant savings is realized by utilizing a smaller number of higher capacity burners. A reduction in the number of burners is required to satisfy the DMB design criteria without changing the furnace width as discussed earlier in this section. In the Case B design, no savings can be assumed for a reduction in burner quantity.

TABLE 6-1. TERMINAL POINTS

Support Steel for Following Equipment

NOTE: Foundations, column base plates and anchor bolts are furnished by PURCHASER

Hangers and rods, nuts, and washers and bearing plates for support of drums, headers and tubes at top of unit

Horizontal support steel for support of drums, headers, and tubes at top unit, not including top framing of boiler columns

Miscellaneous Terminal Points

Blank connections at wall boxes for future soot blowers
Thermometer well connections as required
Draft connections as required
Air measurement connections as required
Blanked test connections for air and gas traverses

Piping

The PURCHASER furnishes all piping external to the boiler.

Safety valve relief piping to 8 ft. above top steel
Power control valve piping to 8 ft. above top steel
Water gauge and/or column drain piping terminating at a valve located at operating floor level
Drum pressure gauge to operating floor level
Piping for air motor drives for soot blowers from manifold at side of boiler
Air seal and aspirating air piping

The following Equipment is Furnished by the Purchaser within Terminal Points Listed:

Flue from economizer to primary and secondary air heaters
Air duct from primary and secondary air heaters to rear boiler columns
Steam coil air heaters

The Following Equipment is Furnished. To Be Installed By The Purchaser Within His Work:

Soot blower control panel for mounting on PURCHASER's control panel
Reheat attemperator sleeve and spray nozzle to be installed in PURCHASER's piping
Non-return valve
Power control valve
Superheater safety valves
Reheater safety valves

TABLE 6-2. CASE A DMB COST IMPACTS

Burners	$<244,800.00>
Furnace Wall Panels	$ 120,000.00
Windbox Division Plate	$ 33,150.00
Controls:	
Air Foil Flow Meters	$ 6,500.00
Dampers	$ 32,060.00
Damper Drives	$ 42,625.00
P Transmitters	$ 11,700.00
System Modifications	$ 1,600.00
Miscellaneous	$ 1,725.00
TOTAL COST DIFFERENTIAL	$ 4,560.00

NOTE: Costs are intended to show trends and "order-of-magnitude" only. Individual applications will have to be priced in detail to determine the economic impact of DMB application.

TABLE 6-3. CASE B DMB COST IMPACTS

Burners	$ <18,000.00>
Furnace Wall Panels	$ 120,000.00
Compartmented Windbox	$ 975,000.00
Controls:	
Air Foil Flow Meters	$ 6,500.00
Dampers	$ 32,060.00
Damper Drives	$ 42,625.00
P Transmitters	$ 11,700.00
System Modifications	$ 1,600.00
Miscellaneous	$ 1,725.00
TOTAL COST DIFFERENTIAL	$1,173,210.00

NOTE: Costs are intended to show trends and "order-of-magnitude" only. Individual applications will have to be priced in detail to determine the economic impact of DMB application.

Furnace Wall Panels

The cost of the furnace wall panels required for a DMB firing system will increase due to additional engineering and fabrication costs associated with the addition of tertiary air ports. The change in material cost is negligible. The difference in cost for producing the DMB panels compared to the NSPS base case panels is approximately $60,000/wall or $120,000 for both opposed-fired (front and rear furnace walls) boiler designs. This cost consists of approximately 85 percent additional material and fabrication cost and 15 percent additional engineering cost.

Windbox

The windbox modification described earlier is a fundamental part of the DMB firing system design. In review, the modification required to direct air flow independently to the burner throats and tertiary air ports includes dividing the windbox vertically in addition to the conventional horizontal divisions (available only in the Case A design). Carbon steel plates will be utilized for the vertical windbox partitions. The cost differential for the windbox modifications required for the DMB application on the base Case A boiler design is approximately $33,150. Approximately 2/3s of that amount is material cost and 1/3 engineering cost. The two different windbox designs are indicative of the design approaches taken by two different manufacturers. Each has its own particular advantages and disadvantages. There are no other equipment or O&M costs that are impacted by the differences in windbox design.

The modifications required for the Case B design are considerably more extensive. In addition to the modifications required for the Case A design, additional ductwork, horizontal division plates, dampers, and air flow measurement modifications must be provided. The additional cost for these modifications, including engineering, erection, and materials, is on the order of $975,000. While it was clear with the Case A boiler design that the windbox partitioning was the most cost-effective method of controlling burner and tertiary air port air flows, other alternatives (individual tertiary port dampers or supply ducts, etc.) should be evaluated for the Case B design.

Controls

The measurement and control of the burner and tertiary air port air flows requires the addition of two metering devices (in this case air foils) and two control dampers for each burner elevation. The additional control elements required include a pressure differential transmitter for each air foil metering device added (in this case 12) and a damper drive for each tertiary port control damper (also 12). It may be possible to eliminate the extra control damper drives by linking the tertiary port dampers with the burner damper drives. However, at least for the first few boilers designed with the DMB system, the additional operating flexibility provided by the separate damper drives should be incorporated.

With respect to the control system itself, the cost impact of the addition of the tertiary port control damper logic to the balance of the firing controls would be minimal ($1,600). With most modern digital control systems, the modification could simply be added to the system control program without any hardware changes.

The cost impact of the control system modifications required (including the additional drives) is approximately $94,485.

These costs are assumed to be the same for both Case A and B boiler designs. The difference in windbox modification cost described earlier provides an equivalent arrangement from which to base the control modifications required.

Erection

The addition of a DMB firing system as part of a new utility boiler design would not significantly impact the erection cost of that boiler based on the information generated in this economic review. The decreased number of burners would actually reduce erection labor required for burner installation (Case A only). The same is true, to a lesser extent, for the labor required to hang the furnace wall panels. Those reductions, however, will be more than offset by the increased labor required to install the DMB windbox (particularly for the Case B design). The additional measurement and control elements, but primarily the vertical partition plates, will increase erection labor requirements.

The combination of the various labor impacts will probably result in a slight increase in the total labor required for the boiler erection but it will only be a minor amount in the Case A design arrangement. The labor required to erect the windbox for the Case B design will increase significantly but the economic impact was included in the cost figure shown in Table 6-3.

Operating and Maintenance Impacts

While there will be slight increases to maintenance costs projected for DMB-fired boilers (additional dampers, drives, etc.) the cost impact will be minimal.

However, based on carbon losses observed during laboratory and field testing of the DMB to date, a significant operating cost impact could be projected. Using the 625 MW_e boiler example:

Coal Flow $\approx$ 500,000 lb/hr
Coal Heating Value $\approx$ 12,000 Btu/lb
Coal Ash $\approx$ 10 percent
Boiler Capacity Factor $\approx$ 65 percent
Coal Cost $\approx \$1.50/10^6$ Btu

Figure 6-16 illustrates the operating cost (fuel value only) incurred due to carbon losses in the boiler flyash and bottom ash. Additional costs must be considered due to the extra fuel and ash handled as the carbon loss

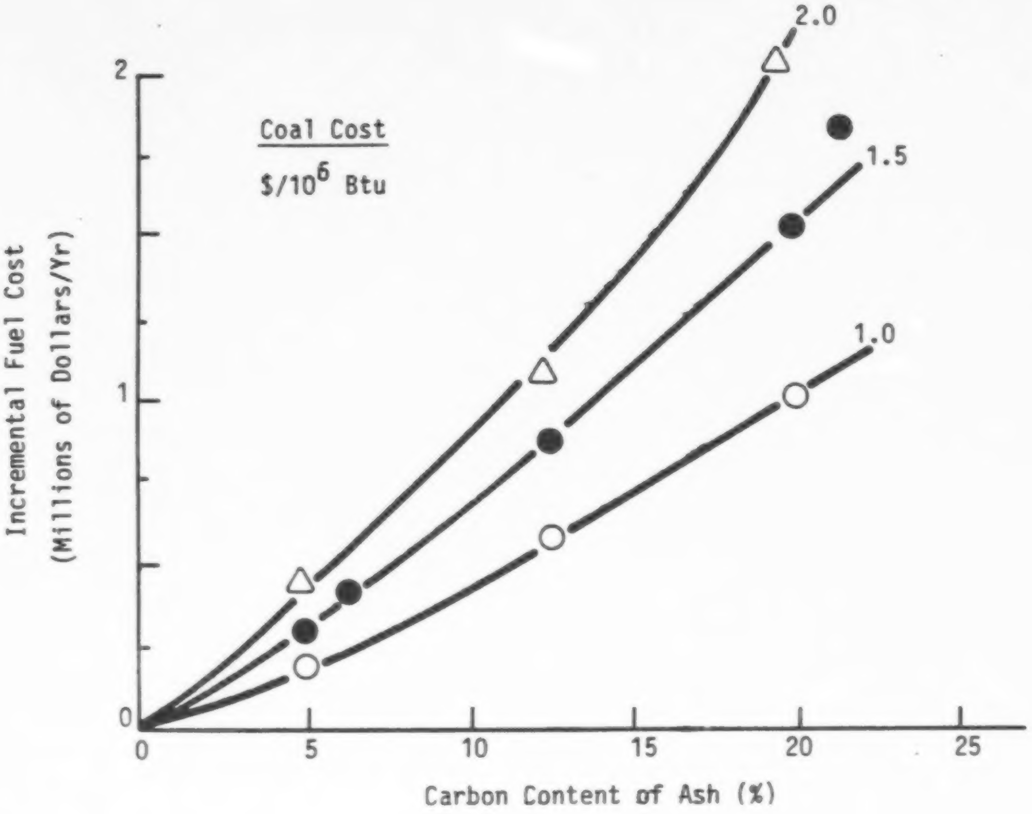


Figure 6-15. Operating cost impact due to carbon loss.

levels increase. Using conventional NSPS burners, the carbon content of the ash should be below 10 percent content.

There is not enough large-scale DMB operating data available to predict the increases in carbon losses, if any, that may result from the DMB application.

6.2 Applicability of DMB Retrofits to Existing Utility Boilers

The design, installation, and operation of the DMB firing system at WIPCO's Pearl Power Station was a valuable demonstration of its applicability to industrial and small utility pulverized coal-fired boilers. It also provided insight for applying the technology to larger utility boilers. As the boiler size increases and the steam cycle demands higher temperature and pressure boiler operation, the design complexity increases. This same complexity increases the amount of study required to fully evaluate the retrofit of the DMB system to larger boilers. Certainly for every retrofit application, a detailed engineering study will be required. This report can only identify those areas of concern that should be studied and convey any information derived from the program that may make those studies more meaningful.

Boiler design depends on size, manufacturer, outlet steam conditions required, age, structural configuration, and many other factors. Each boiler will present a unique set of challenges to retrofit the DMB firing system. However, in virtually all retrofit situations, space limitations and physical interference with existing equipment will be the primary impediment to the DMB retrofit. The simple burner/windbox designs, incorporated in pre-NSPS boiler designs, are difficult to adapt economically to the DMB system. The approach taken at Pearl Station, replacement of the firing wall and windbox, appears to be the cost effective one in most cases. It may be assumed that most smaller (<100 MW_e), single wall fired boiler retrofits will generally parallel the Pearl Station modifications quite closely.

The following are areas of concern that any potential retrofit candidate will face:

- Insufficient space between burners for tertiary air ports (inadequate furnace width)
- Inadequate furnace depth if increased flame length results
- Interference with windbox platforms and support steel
- Insufficient windbox depth for good air flow distribution to the burners and tertiary air ports
- Interference with coal piping
- Interference with downcomer piping
- Inadequate water circulation in the firing walls
- Insufficient firing wall structural length after DMB retrofit.

6.2.1 Furnace Size

In nearly all retrofit situations, the candidate boiler furnace width will not be adequate for retrofitting the same number of DMBs as original burners while maintaining the proper relationship of the tertiary air ports to each burner. Modification of the existing furnace size will, in most cases, be completely out of the question. Instead, a DMB retrofit will require some compromise of the design parameters usually coupled with a reduction in the number of burners. This should not present any significant difficulty on larger boilers with burner elevations consisting of five or more burners, providing that the flames from the larger burners can be accomodated in the furnace.

Retrofit candidates that utilize firing elevations with less than five burners may require more severe compromises of the DMB design parameters. Various aspects of the tertiary air port shape and location should be considered to minimize burner spacing and therefore furnace width requirements. The approach to making design parameter compromises is addressed in Subsection 6.2.5.

The furnace depth becomes a concern, particularly on smaller, single-wall fired boiler designs, because of the increased flame length that may result as a consequence of the DMB application. The flame length of the DMB can be adjusted to match that of the pre-NSPS burner design it replaces. However, by reducing the number of burners to enable the existing burner width to be utilized as discussed above, the heat input/burner will be increased. Flame length is a function of heat input and can usually be expected to increase as the heat input/burner increases. This effect may be offset by additional DMB adjustments to reduce flame length.

6.2.2 Physical Interferences

Many of the interference problems faced in any retrofit situation may be alleviated without a great deal of effort. Interferences such as cable trays, platform and stairway steel, plant utility air and water piping, etc. are examples. However, structural steel members can seldom be relocated without a great deal of expense.

In general, the DMB tertiary air port and boiler structural steel locations will determine the location of the balance of the windbox components. Most retrofits will be most economically completed by the redesign and replacement of the windbox entirely. Structural steel may also limit the maximum depth of the retrofit windbox. The increased number of burner registers and tertiary port air flow requirements may overcrowd the windbox causing flow distribution problems. This situation could contribute to higher unburned carbon losses.

Interferences with downcomer piping will occur only on higher pressure boilers without convective section boiler banks. The smaller, low pressure units will usually utilize downcomer piping in the rear of the boiler, away from the firing wall and retrofit area. In contrast, the majority of downcomer piping on larger boilers is located near the front wall, many times routed through the windbox itself. This piping generally has a minimum nominal diameter of 12 inches and very thick walls.

Even supercritical, "once through" designs, which do not utilize a steam drum with several large downcomers for liquid recirculation, have numerous, smaller downcomers to supply the various furnace circuits which must be considered. In addition, those designs often have large mixing headers located at various locations adjacent to the furnace which would be extremely expensive to relocate.

While rerouting downcomer piping is not impossible, it is a very costly modification.

6.2.3 Waterside Circulation

The possible impact on waterside circulation in the firing walls should be evaluated. Due to the increased number of tube bends required to locate the tertiary air ports in the firing walls of the candidate boiler, the resistance to flow of the steam/water mixture inside the bent tubes increases. If the flow resistance becomes high enough, the flow will drop below the minimum required to keep the tube from overheating, and consequently, failing. This concern becomes increasingly important as the design pressure of the boiler increases. In higher pressure designs, the difference in specific volume between saturated vapor and liquid is less, therefore the natural circulation head in the boiler tube circuits is lower. It is this circulation head pressure that causes waterside circulation to occur, unassisted, in all natural circulation boiler designs.

6.2.4 Structural Considerations

The DMB installation experience at the Pearl Station is exemplary of the structural considerations that must be addressed for any DMB retrofit. The primary impact of the DMB design on the structural system is related to the number of tubes bent in the firing walls for the tertiary air ports. The tubes which are bent to form openings in the furnace wall are no longer considered to have any significant load carrying capability. Therefore, if the number of straight tubes that remain to support the lower portion of the boiler wall and hopper slope is inadequate, other methods must be employed to support that weight. Subsection 6.2.5 addresses tertiary port design alternatives which can minimize the number of wall tubes requiring bending.

It is reasonable to expect that most industrial DMB retrofits would require very similar structural modifications to the Pearl unit. Relatively small furnaces with single wall firing should have enough strength in the sidewalls to carry the additional loads.

As boiler size increases, the loads encountered as a result of heavier wall tubes, additional burners and tertiary ports, and firing from two walls may not simply be transferred to the side walls. Another means of support such as spring hangers attached to the main structural members or lower furnace support from grade will have to be employed.

It may also be necessary to verify that the boiler support columns can handle the additional loads. Additional support steel may be necessary in some cases.

6.2.5 Retrofit Compromises

The initial approach to DMB application should be based on the design parameters listed in Section 2.0. In most retrofit situations it will be necessary to make some design decisions that will result in a retrofit DMB firing system that does not exactly conform to these parameters. This will possibly result in less than optimum NO_x emissions performance. However, the decrease in emissions performance may be small enough to enable the retrofit boiler to achieve the desired emissions goal. This section will discuss some of the possible compromises and design alternatives available for applying the DMB to existing boilers.

Tertiary Port Design

The design of the tertiary ports significantly impacts the furnace width required for the DMB firing system. At the same time, the port shape determines the number of wall tubes that require bending and consequently, impacts retrofit costs, waterside circulation, and structural considerations as discussed above. The first compromise to the DMB design parameters considered should be the design of the tertiary ports due to the close burner to burner spacing in virtually all multiple burner applications, the design should assume that ports are shared between each two burners in the horizontal direction. This will reduce the furnace width required for DMB retrofit. The impact of port sharing is discussed further in Subsection 6.1.4.

Figures 6-17 through 6-20 illustrate a section of boiler furnace wall area that accommodates the DMB design approach. Each shows two burner throat openings in the wall and associated thertiary air port popenings. A few of the tubes that form the wall are shown for illustrative purposes. The wall openings are formed by bending tubes out of the plan of the wall and to the sides. In each figure, the flow area of the tertiary port openings are equivalent to those shown in the other figures.

Figure 6-17 shows the circular tertiary port arrangement which was used during the development of the DMB and, subsequently, for the WIPCO retrofit. The round configuration represents the "worst" case from the number of tube bends required to achieve the desired flow area. The first compromise to consider for reducing the number of wall tubes bent is that of port shape. Figures 6-18 through 6-20 illustrate several alternative port arrangements that reduce the number of bent tubes required while maintaining the DMB port parameters for flow rate and velocity.

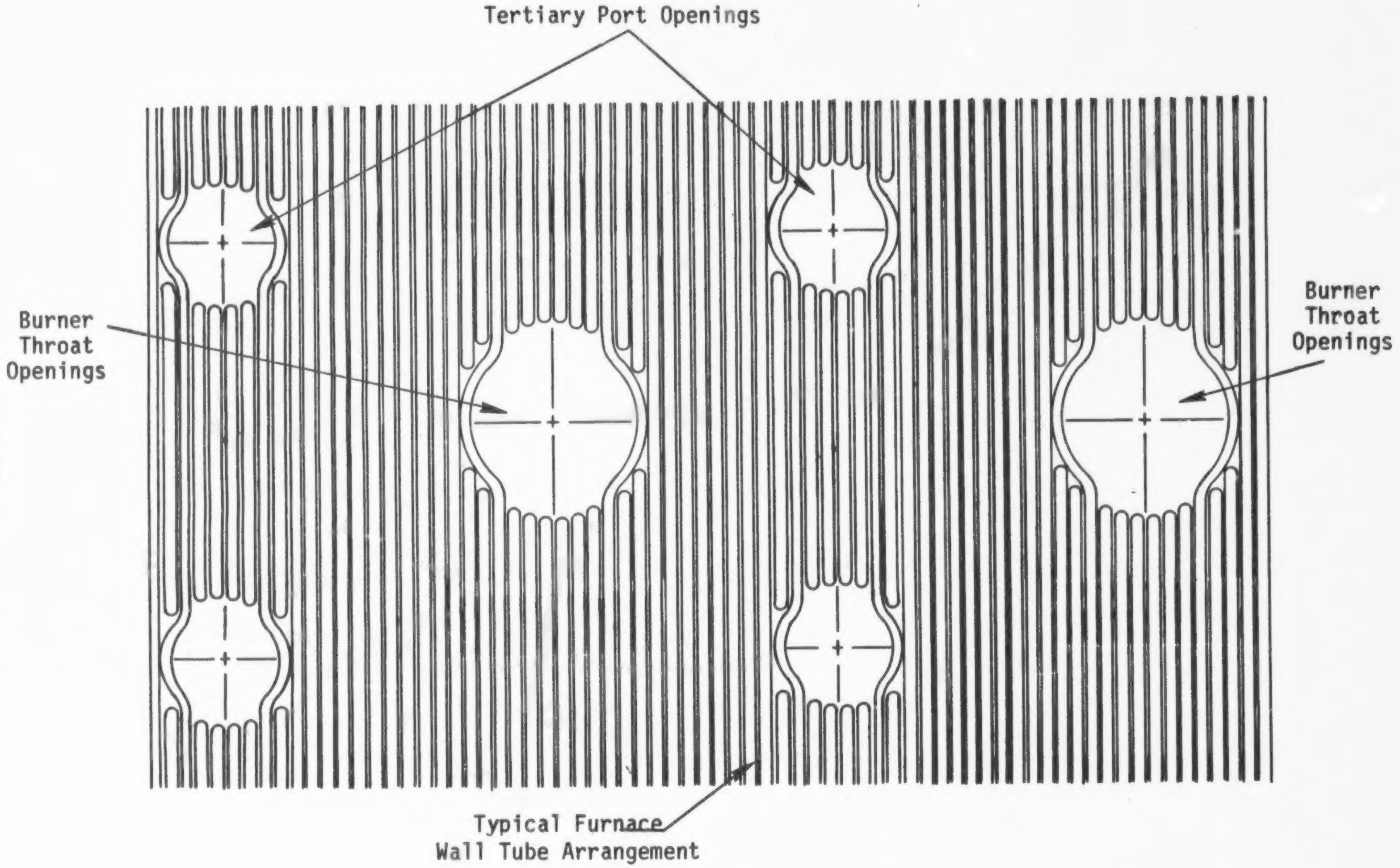

Tertiary Port Openings
Burner Throat Openings
Burner Throat Openings
Typical Furnace Wall Tube Arrangement

Figure 6-17. Circular tertiary port design.

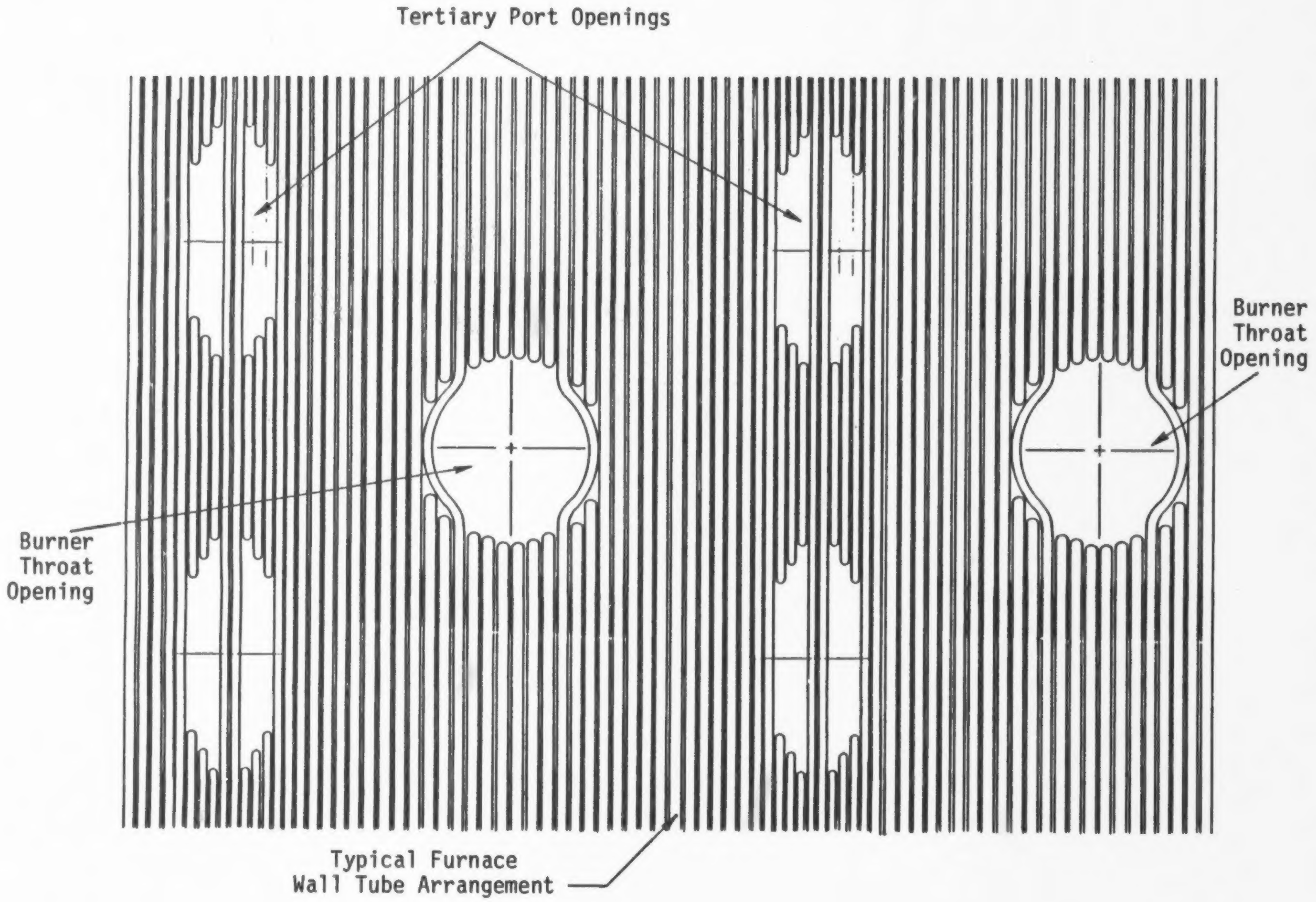

Tertiary Port Openings
Burner Throat Opening
Burner Throat Opening
Typical Furnace Wall Tube Arrangement

Figure 6-18. Slightly elongated tertiary air port with division.

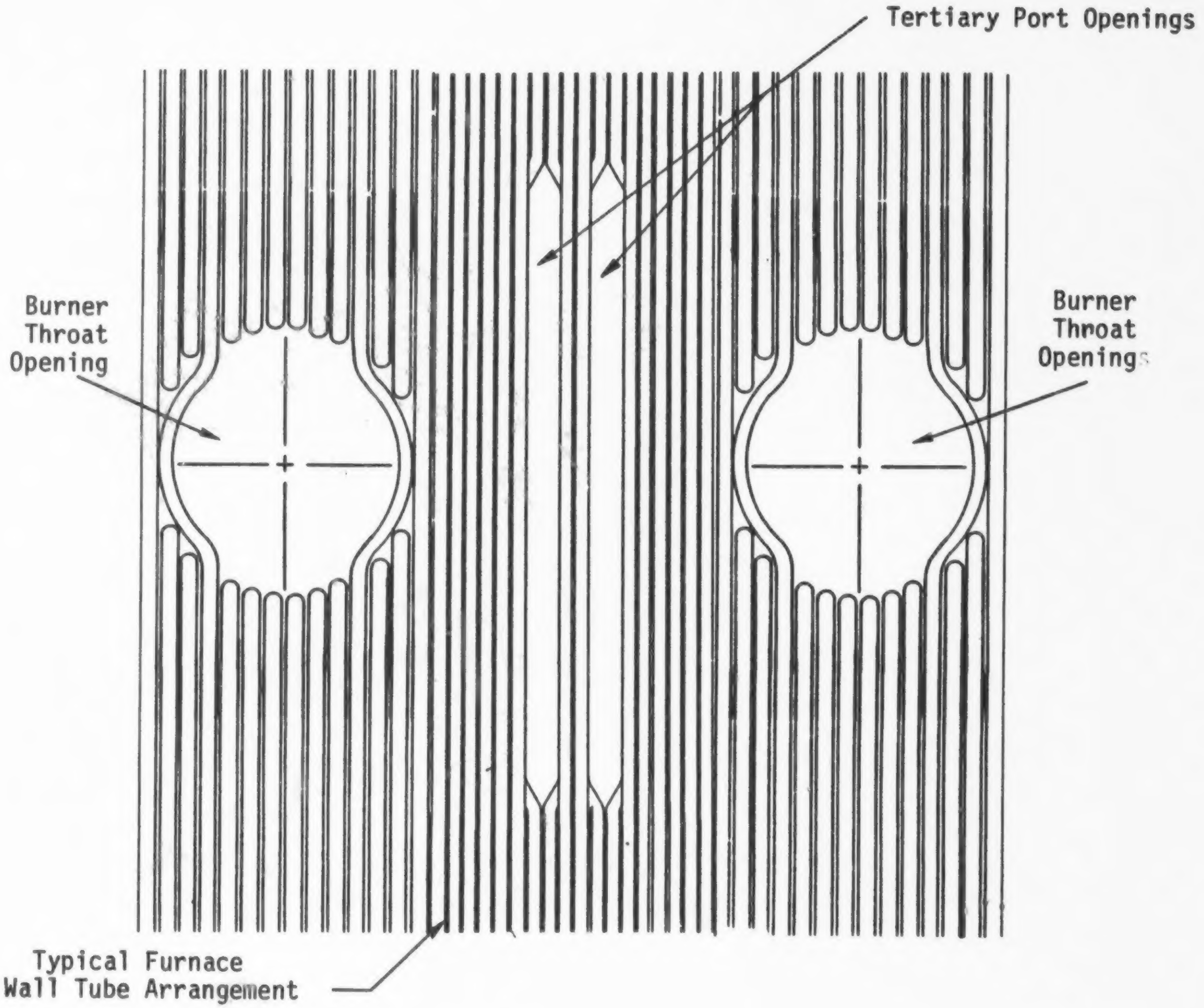

Tertiary Port Openings
Burner Throat Opening
Burner Throat Openings
Typical Furnace Wall Tube Arrangement

Figure 6-19. Elongated tertiary air port design with division.

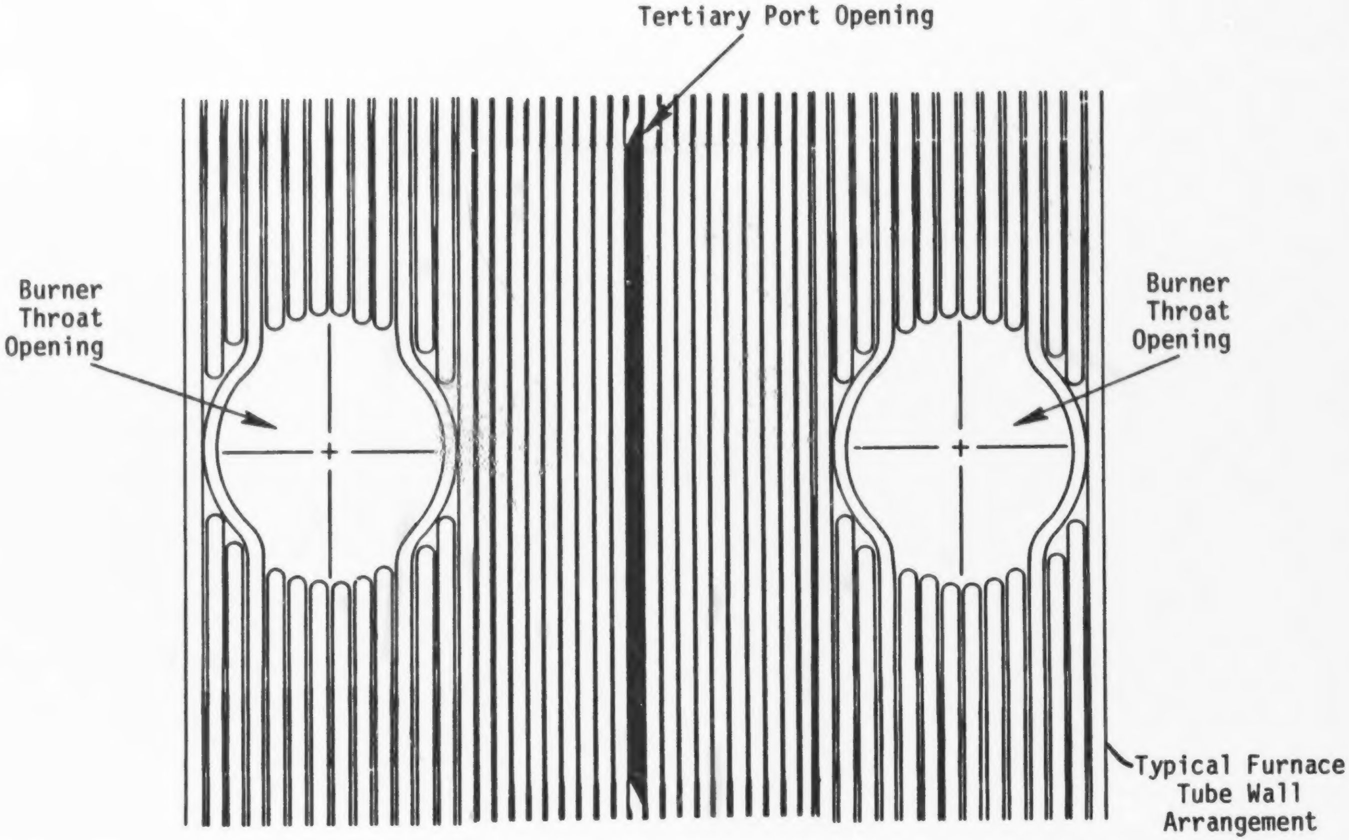

Tertiary Port Opening
Burner Throat Opening
Burner Throat Opening
Typical Furnace Tube Wall Arrangement

Figure 6-20. Elongated shared tertiary air port design.

A second compromise which should be considered is that of port location. The burner spacing and furnace width required are directly effected by the radial distance between the tertiary ports and the burner throats. Development testing of the DMB concept has shown that, as the distance increases, NO_x emissions decrease. Other factors such as burner carbon conversion efficiency, practical constraints on flame length, the probability of contact between furnace wall surfaces and reducing gases, have lead to the decision to limit the port radial distance to 2.2 throat diameters. In the typical retrofit case, with close burner spacing a compromise must be made to reduce the distance to the tertiary ports. Previous small-scale DMB testing indicates that the ports should not be located closer than 1.5 throat diameters from the burner centerline or NO_x emission reduction becomes ineffective.

Based on the results of the isothermal tertiary air port mixing study and the results of the full scale field evaluation at WIPCO, the burner to burner spacing and design of the tertiary air port array may have major impacts on the ability to balance the burners. Flow mixing tests should be incorporated into the design process to minimize any tendency for non-uniform tertiary air entrainment. The preferred approach is to avoid shared ports if possible. If shared ports are required, the tertiary velocity should be increased to reduce imbalance problems.

Burner Throat Design

The reduced secondary air flow rate and reduced secondary velocity of the DMB compared to conventional burners generally result in DMB throat diameters comparable to conventional pre-NSPS burners, this suggests a very low cost approach to DMB retrofit: no changes to the existing burner throat. Small deviations from the DMB design velocities would probably not be significant. However, the burner flame stability should be evaluated in a fired test. Throat sizes for DMBs are discussed in Subsection 6.1.4.

6.3 NO_x Emission Projections

6.3.1 Analysis of Research Furnace Data

In this and previous EPA programs, several DMB configurations were tested in a number of research furnaces. In some cases, one burner configuration was tested in two furnaces. In others, burners of similar design but different scale were tested in a single furnace. This subsection provides an analysis of these data focusing on the effects of burner scale and furnace confinement on NO_x emissions.

The data base is shown in Table 6-4. The first comparison involves three scales of development DMBs fired in one furnace and one scale of a similar burner design fired in a second furnace. Comparison 2 involves the initial prototype DMB fired in two furnaces and Comparison 3 involves the final prototype DMB fired in two furnaces. Comparison 4 involves the versatile DMB (being developed under EPA Contract 68-02-3667) fired in a research furnace with variable heat extraction. The following subsection presents the designs of the burners and research furnaces and the second subsection discusses the test results and comparisons. The last subsection summarizes the results and presents conclusions relative to burner scale and furnace confinement effects.

Equipment

The following burner designs were tested:

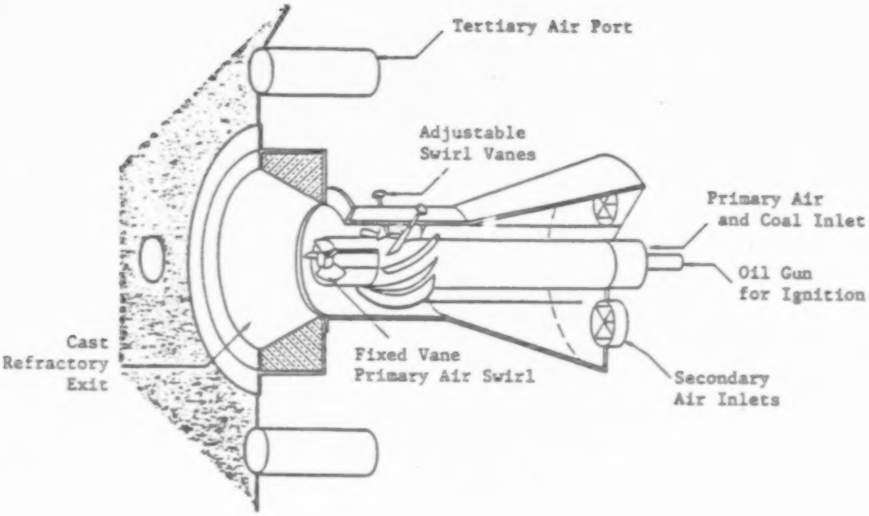
- Single Secondary Development DMBs - 12.5, 50 and 100 x 10^6 Btu/hr
- Initial Prototype DMB - 70 x 10^6 Btu/hr
- Final Prototype DMB - 70 x 10^6 Btu/hr
- Versatile DMB - 12.5 x 10^6 Btu/hr

The design of the Single secondary Development DMBs is illustrated in Figure 6-21A. They have central coal nozzles and single concentric secondary air passages with swirl vanes. This burner design was constructed in three

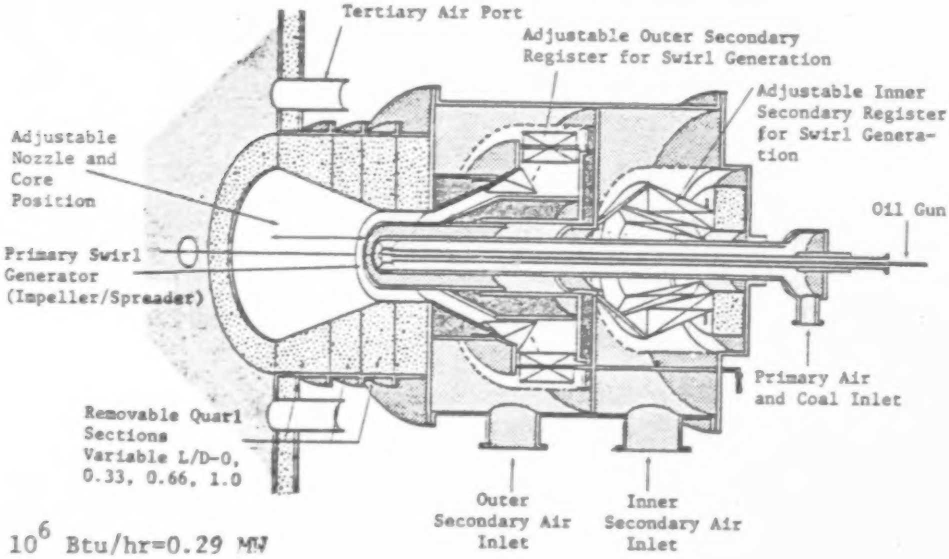
TABLE 6-4. DATA BASE

COMPARISON NUMBER	BURNER	CAPACITY 10^6 Btu/hr	FURNACE
1	Single Secondary Development DMBs	100 50 4 x 12.5	Old LWS
		12.5	Old SWS
2	Initial Prototype DMB	70	Old LWS New LWS
3	Final Prototype DMB	70	New LWS MT
4	Versatile Burner	10	New SWS

Note: 10^6 Btu/hr = 0.29 MW


Tertiary Air Port
Adjustable Swirl Vanes
Primary Air and Coal Inlet
Oil Gun for Ignition
Cast Refractory Exit
Fixed Vane Primary Air Swirl
Secondary Air Inlets

A. Develop DMBs (12.5, 50 and 100 x 10^6 Btu/hr).


Tertiary Air Port
Adjustable Outer Secondary Register for Swirl Generation
Adjustable Inner Secondary Register for Swirl Generation
Adjustable Nozzle and Core Position
Oil Gun
Primary Swirl Generator (Impeller/Spreader)
Primary Air and Coal Inlet
Removable Quarl Sections Variable L/D-0, 0.33, 0.66, 1.0
Outer Secondary Air Inlet
Inner Secondary Air Inlet

Note: 10^6 Btu/hr=0.29 MW

B. Versatile burner (12.5 x 10^6 Btu/hr capacity).

Figure 6-21. Research DMBs.

scales using constant velocity and geometric scaling. The 12.5 x 10^6 Btu/hr scale was chosen so that a 2 x 2 array of burners could be tested in place of a single 50 x 10^6 Btu/hr burner to provide an evaluation of burner scale independent of furnace confinement effects. These burners were research designs and did not incorporate commercial burner components.

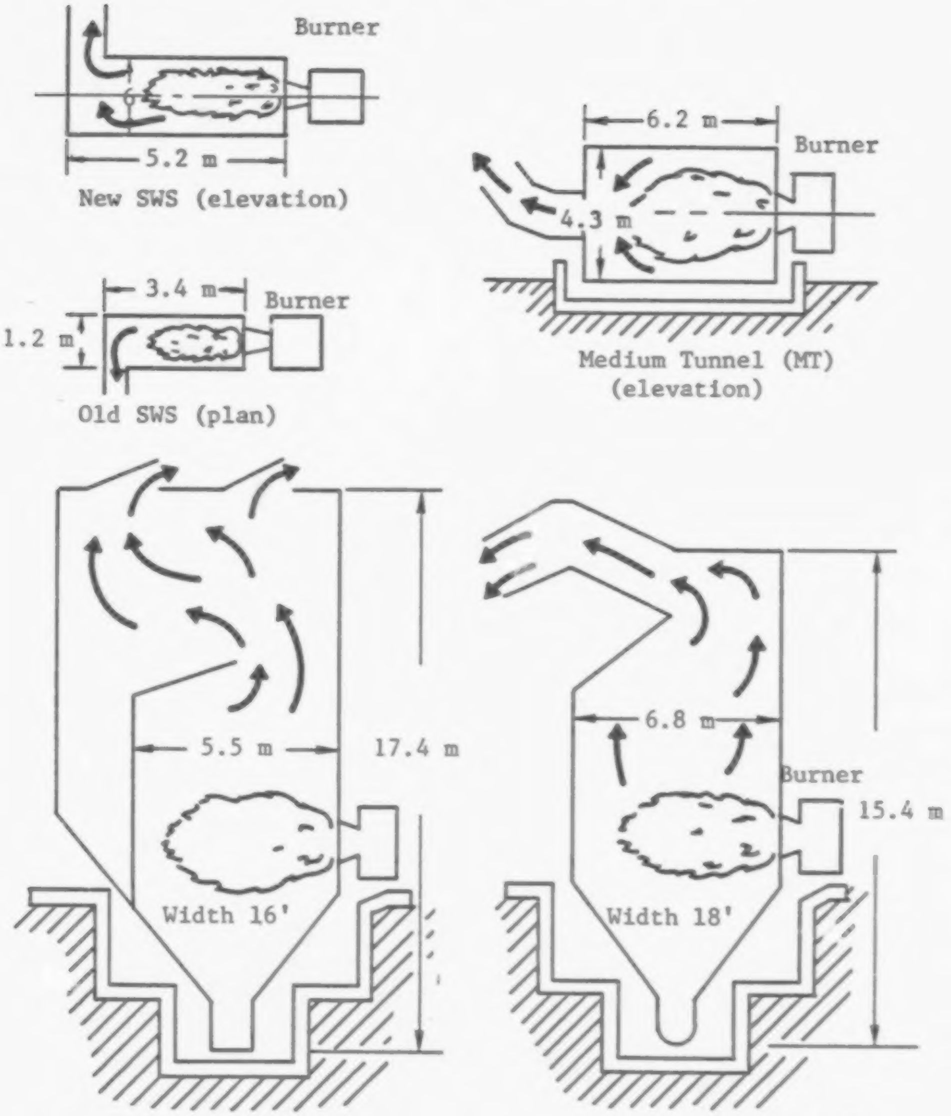
The prototype DMBs were designed by integrating the DMB design criteria (the parameters which resulted in optimum performance with the development DMBs), Foster Wheeler burner components and the requirements of the WIPCO host boiler. The initial prototype DMB was designed by modifying the exit geometry specified by the design criteria to meet WIPCO windbox depth limitations. The final prototype DMB incorporated Foster Wheeler Controlled Flow Burner exit geometry. Both prototype DMBs have annular coal nozzles and dual secondary air passages with registers for swirl control. Other details of the prototype burner design were discussed in Section 3.

The Versatile DMB is shown in Figure 6-21B. This research burner is being used to evaluate the effects of burner parameters on overall burner performance under EPA Contract 68-02-2667. It has a central coal nozzle with an impeller/spreader. Secondary air is supplied through two annular passages with registers for flow rate control.

The DMBs were tested in the following research furnaces:

- Old Small Watertube Simulator (old SWS)
- New Small Watertube Simulator (new SWS)
- Old Large Watertube Simulator (old LWS)
- New Large Watertube Simulator (new LWS)
- Medium Tunnel (MT)

The designs of these furnaces are shown in Figure 6-22 and Table 6-5 compares the design and operating parameters. Additional details are presented in Appendix A of Volume 2.


Burner
5.2 m
6.2 m
Burner
4.3 m
3.4 m
Burner
1.2 m
5.5 m
17.4 m
Width 16'
6.8 m
Burner
15.4 m
Width 18'

New SWS (elevation)

Medium Tunnel (MT) (elevation)

Old SWS (plan)

Old LWS (elevation)

New LWS (elevation)

Figure 6-22. Research furnaces.

TABLE 6-5. RESEARCH FURNACE CHARACTERISTICS

FURNACE	OLD SWS	NEW SWS	OLD LWS	NEW LWS	MT
Shape	Rectangular	Horizontal cylinder	Rectangular with hopper and nose	Rectangular with hopper and nose	Horizontal cylinder
Firing Configuration	End	End	Front wall	Front wall	End
Exhaust	Side-rear	Top-rear	Top	Top	End
Firing Capacity (Btu/hr)	15×10^6	15×10^6	125×10^6	150×10^6	80×10^6
Width (ft)	4	6 (dia)	16	16	14 (dia)
Firing Depth (ft)	11	17	18	22	20
Overall Height (ft)	5	-	54	50	-
Cooling	External water spray	External water spray	External water spray	External water spray	External water spray
Refractory Insulation in Burner Zone	Bottom	50% of circumference and 100% of target wall	None	Side walls (from knuckle up 16 ft)	50% of circumference and 100% of target wall
Heat Release/Cooled Surface* (Btu/hr ft^2) at:	66,000	50,000	50,000	100,000	90,000
Burner Firing Rate (10^6 Btu/hr)	12.5	12.5	70	70	50

* Definition in text

Note: 10^6 Btu/hr = 0.29 MW
1.0 ft = 0.30 m

The old SWS was the original small research furnace used for DMB development tests. It was rectangular in cross-section with the burner mounted in one end and the exhaust exiting the other end. All surfaces were water-cooled except for the floor which was insulated with refractory.

The new SWS was designed to replace the old SWS. It is a horizontal cylinder slightly larger than the SWS. The burner is mounted on one end and the exhaust exits the other end. The furnace walls are partially insulated with refractory: axial strips of refractory on the circumference and a full covering of refractory on the rear wall. The new SWS has been fired with the Versatile burner.

The old LWS is the original large research furnace used for the development DMB tests at 50 x 100 x 10^6 Btu/hr. The shape was similar to a small front wall-fired boiler with a hopper bottom and nose above the firing zone. All furnace walls were water-cooled with no refractory insulation. The old LWS was used for the development DMBs and the initial prototype DMB tests.

The new LWS was designed to replace the old LWS. The geometry is similar but the furnace sidewalls are insulated with refractory. The initial and final prototype burner were tested in the new LWS.

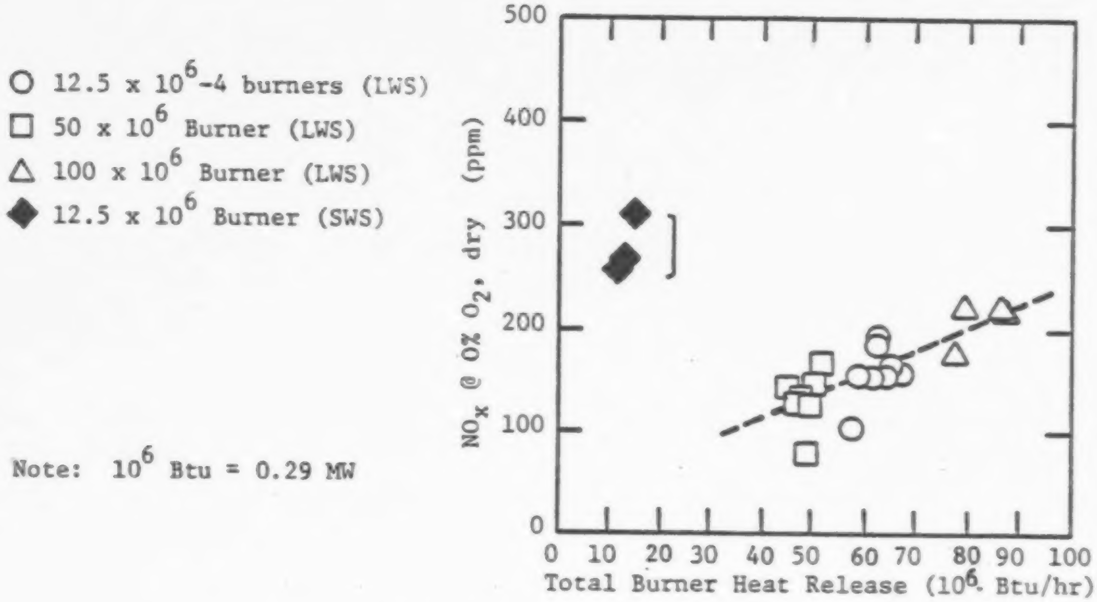
The MT is a horizontal tunnel furnace similar to the new sws in construction but considerably larger. It was used to test the initial and final prototype burners.

These five furnaces provide a range of geometries and also a range of thermal environments. One index of the thermal environment is the heat release per cooled surface area in the flame zone (Q/A). Furnaces with high Q/A have low heat extraction and hence higher effective flame temperatures. Table 6-5 lists Q/A for the research furnaces at the firing rates used for a majority of the tests. For the old and new SWS and MT, the cooled surface area was the furnace surface area nor covered with refractory. For the old and new LWS, which have a structure similar to a boiler, the cooled surface area was the plan area above and below the burner zone and the sidewall area from the knuckle to 10 ft above the burner centerline. (This is the same surface area used in Foster Wheeler's Burner Zone Liberation Rate calculation). It should be note that Q/A is an approximate indication of heat extraction. Other parameters such as furnace shape and flow characteristics would also be expected to influence heat extraction.

Data Comparisons

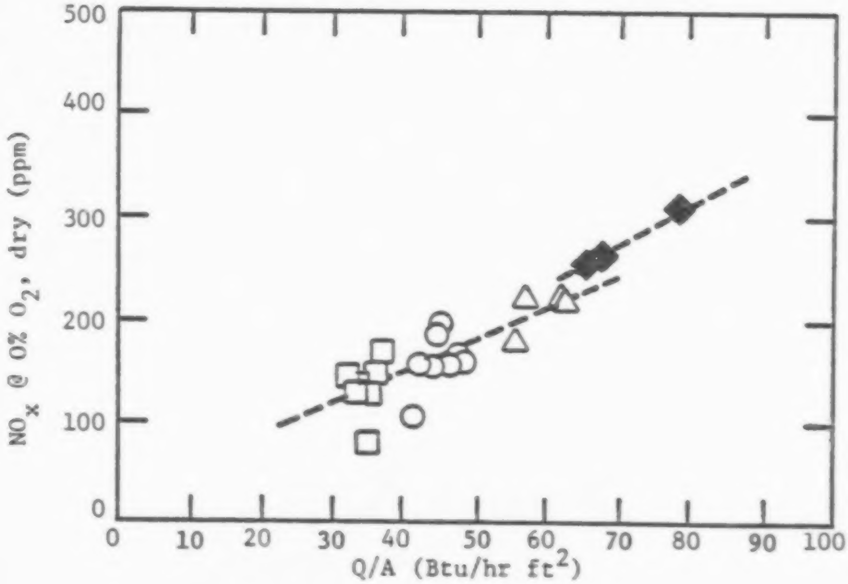
Comparison 1 - Development DMBs in Old SWS and LWS. Three configurations of Single Secondary Development DMBs were tested in the old LWS: 50 and 100 x 10^6 Btu/hr burners were tested individually and 4-12.5 x 10^6 Btu/hr burners were tested as a 2 x 2 array. In addition, a single 12.5 x 10^6 Btu/hr burner was tested in the old SWS. These burners were designed to have the same velocities through the burner passages at full load with similar geometry. Each burner/furnace configuration was tested over a wide range of test conditions. Data obtained at the same conditions (except for firing rate) shown in Figure 6-23. These data provide an evaluation of the burner scaling method, furnace confinement and flame interaction. Figure 6-23A shows NO_x emissions as a function of total heat release. Within some scatter, the data from the LWS tests lie along a single line. This suggests that NO_x emissions are related to total heat release and that the effects of burner scale and flame to flame interactions are small. The SWS data shown in Figure 6-23A do not agree with the LWS data. however, as was shown in Table 6-5 the SWS has a high value of Q/A. These same data are replotted as a function of Q/A in Figure 6-23B. The LWS and SWS data now appear to be very similar. This suggests that for this burner design, the primary parameter influencing NO_x emissions is furnace confinement.

Comparison 2 - Initial Prototype DMB in Old and New LWS. Comparison 1 showed that for constant velocity scaling, the NO_x emissions from DMBs were related primarily to furnace confinement. However, it is important to note that the primary variable was the burner firing rate, not the furnace confinement. Comparison 2 involves tests of one burner, the initial prototype DMB in two research furnaces, the old and new LWS. As shown in



Note: 10^6 Btu = 0.29 MW

A. Effect of total burner heat release.



B. Effect of furnace Q/A.

Figure 6-23. Comparison 1 single-secondary development DMBs in old LWS and SWS.

Table 6-5, the old and new LWS are geometrically similar. The primary difference is the refractory insulation in the new LWS which increases the Q/A by a factor of two.

Figure 6-24 compares the NO_x and CO emissions for the initial prototype DMB in the old and new LWS. This indicates that the refractory insulation in the new LWS provides a hotter thermal environment resulting in improved combustion efficiency. However, NO_x emissions are essentially unchanged. This suggests that for the initial prototype DMB, NO_x emissions are independent of thermal environment over the range investigated.

Comparison 3 - Final Prototype DMB in the New LWS and MT. The final prototype DMB design was fired in the new LWS and the MT. In the MT, the firing rate was limited to about 70 percent of capacity due to flame impingement. The flame filled the MT and extended part way into the exhaust duct. The Q/A for the LWS tests was approximately the same as for the MT tests. However, the net heat extraction was greater in the LWS. Furnace exit temperatures were up to 500°F lower in the LWS.

NO_x and CO emissions are shown in Figure 6-25. In the MT, NO_x emissions are higher and CO emissions are lower than in the LWS. These differences are due to a combination of furnace confinement and thermal environment effects. The smaller size of the MT narrowed and elongated the flame and thus may have altered the mixing of the tertiary air. Since the basis of the low NO_x emissions of the DMB is delayed mixing of the tertiary air, this may have affected NO_x emissions.

Comparison 4 - Versatile Burner in the New SWS. The Versatile burner was tested in the new SWS with variable refractory insulation. In one test the refractory insulation consisted of insulation on the front and rear walls as well as 50 percent of the cylinder surface. In another test, a combination of fire-brick and fiber insulation was used to insulate an additional 40 percent of the cylinder area. The test results are compared in Figure 6-26. The hotter thermal environment had a negligible effect on flame shape but increased NO_x emissions under unstaged conditions (high burner zone

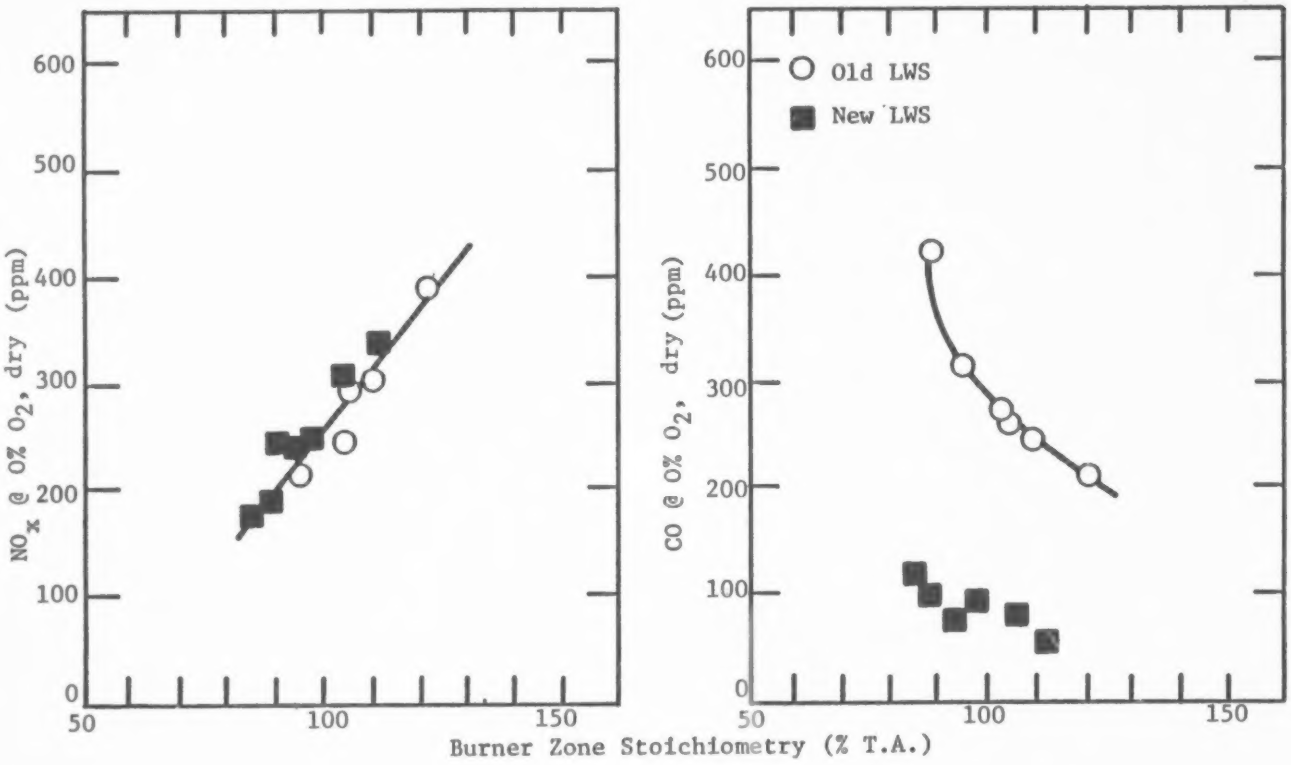


Figure 6-24. Comparison 2 initial prototype DMB in old and new LWS.

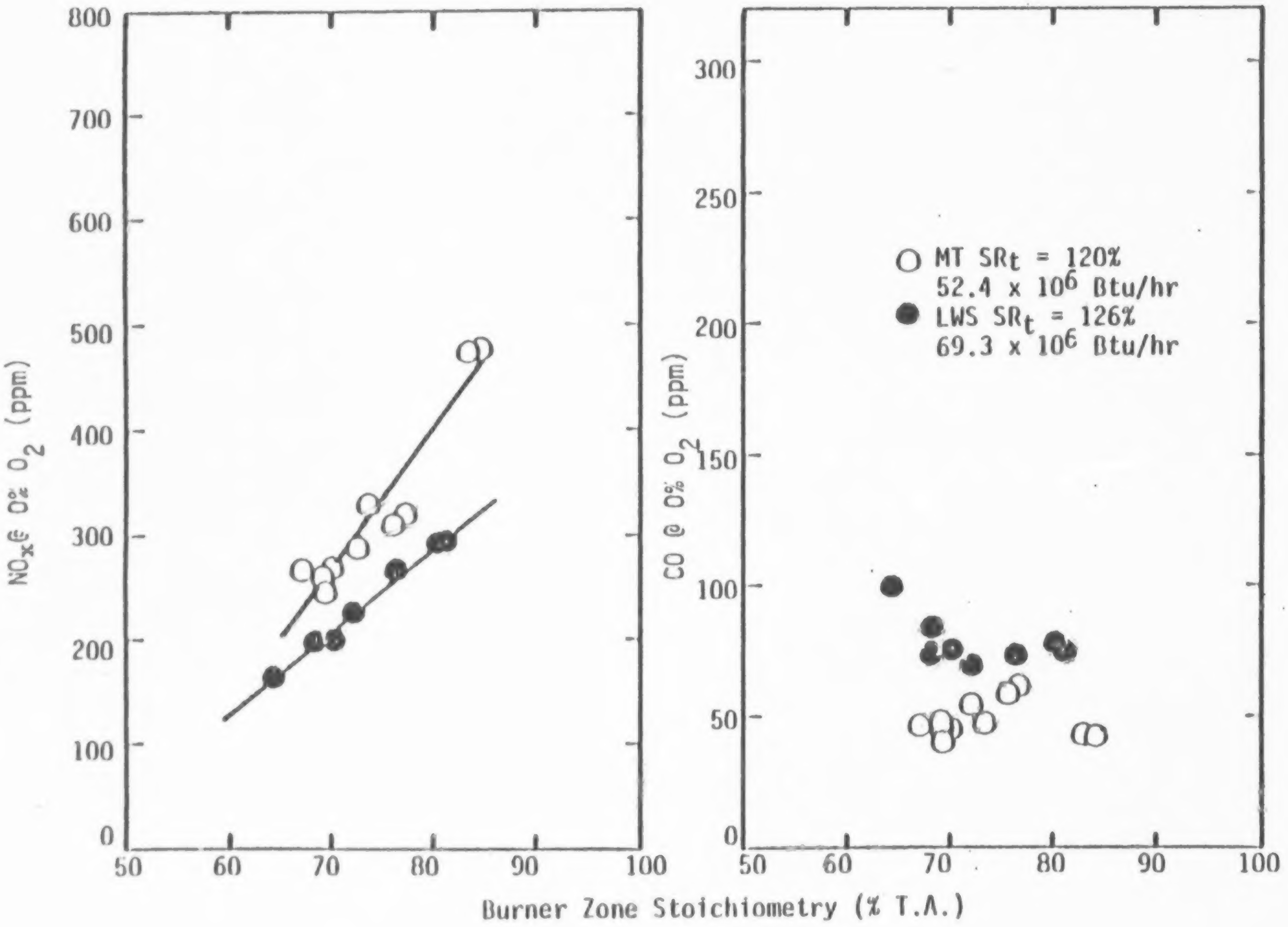


Figure 6-25. Comparison 3 - final prototype DMB in new LWS and MT.

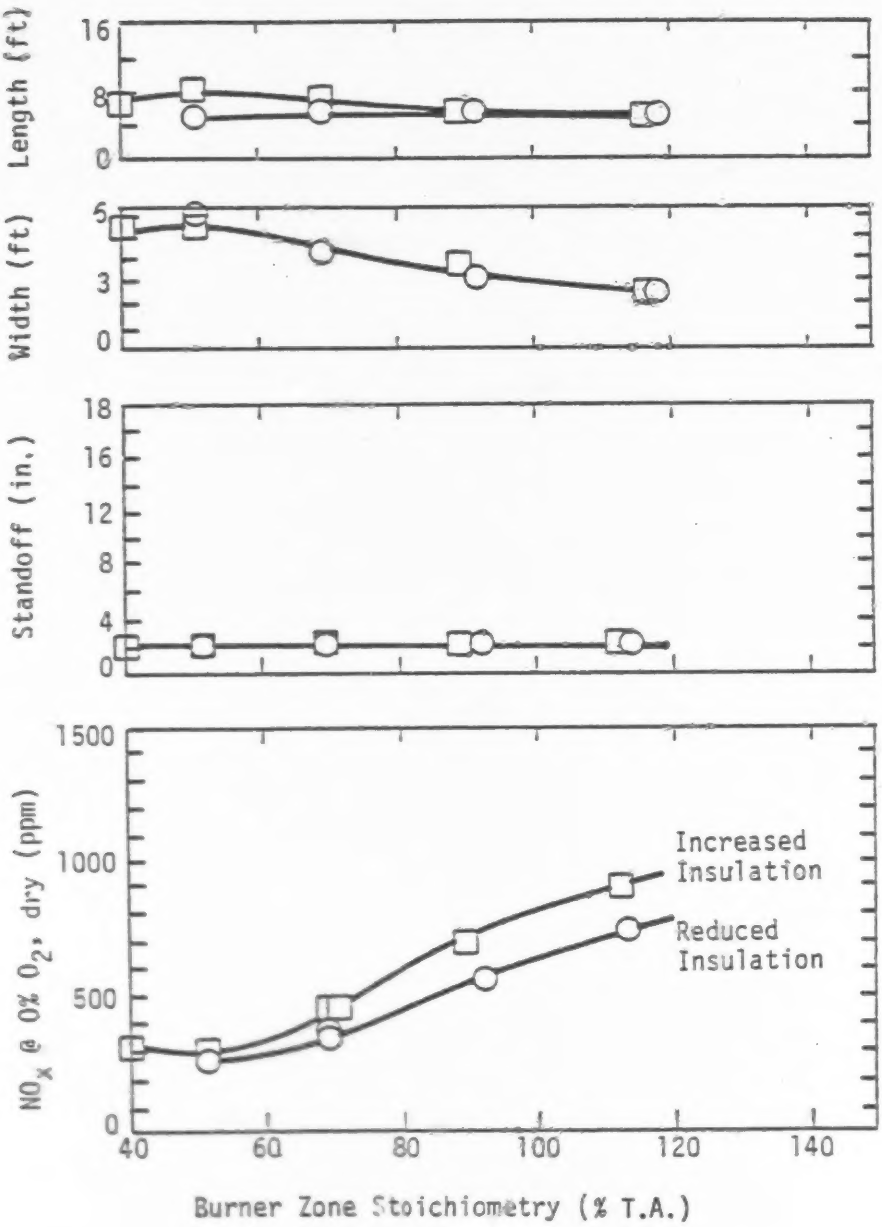


Figure 6-26. Comparison 4 - Versatile DMB in new SWS.

stoichiometry). NO_x emissions were unaffected at low burner zone stoichiometry where the DMB is normally operated.

Influence of Burner Scale and Furnace Confinement on NO_x Emissions

The conclusions reached by evaluating the four comparisons are shown in Table 6-6. Comparison 1 showed that increasing burner capacity in a fixed furnace design resulted in increased NO_x emissions. There was no measurable effect of the flame to flame interaction produced in the 2 x 2 array. NO_x emission were approximately proportional to furnace Q/A. In Comparison 2, increasing the insulation in the furnace with a fixed burner design had no effect on NO_x emissions. In Comparison 3, one burner was tested in two furnaces with similar Q/A but differing furnace volumes. NO_x emissions were higher in the compact furnace. In Comparison 4, increasing the insulation in the furnace had no effect on NO_x emissions at DMB operating conditions but a significant increase resulted under unstaged operating conditions.

In interpreting these results it is important to recognize that the Q/A parameter is an approximate index of heat extraction and comparisons are valid for fixed geometry only. This was illustrated by Comparison 3 where heat extraction was greater in one furnace although the Q/A values for both furnaces were comparable. It is also important to recognize that the range of burner capacity, furnace confinement and number of burners evaluated here does not include the full range of field operating steam generators. Many field operating systems utilize a large number of burner with greater capacity than those tested here in furnaces with lower heat extraction.

6.3.2 Integration of Research Furnace and Field Data

The data analysis presented in the previous subsection indicated that the NO_x emissions from the DMB increase with burner scale but are relatively insensitive to furnace thermal environment providing that the flame is not constrained by furnace walls which distort the fuel/air mixing rates. However, the analysis was based on research furnace data only and the furnace

TABLE 6-6. CONCLUSIONS FROM DATA COMPARISONS

COMPARISON	PRINCIPAL VARIABLE	EFFECT ON NO_x EMISSIONS
1. Development DMBs in old LWS and SWS	Burner capacity	Increase with furnace Q/A flame interactions insignificant
2. Initial prototype DMB in old and new LWS	Furnace insulation	No effect of Q/A
3. Final prototype DMB in new LWS and MT	Furnace confinement	Increase in smaller furnace
4. Versatile DMB in new SWS	Furnace insulation	No effect at DMB conditions, increase at unstaged conditions

thermal environments were "colder" than those of many larger field operating boilers.

The field evaluation at WIPCO provides data in a "hotter" thermal environment. Figure 6-27 is a plot of the research furnace data presented in the previous subsection and the WIPCO operation at full load with optimum burner settings as a function of furnace thermal environment. Foster Wheeler's burner zone liberation rate (BZLR) was used as the thermal parameter. For comparison, Foster Wheeler's published correlations for the pre-NSPS intervane burner have been shown also.

The DMB NO_x emission data are in the range of 0.1 to 0.3 lb/10^6 Btu. The WIPCO data are at the hottest thermal environment but are comparable to the highest NO_x emission data in the coldest research furnace, the old LWS. This confirms that the thermal environment has little effect on NO_x emissions, at least over the range of these data.

The DMB has not been tested in furnaces with BZLR greater than that of the WIPCO boiler. Therefore, NO_x emissions for DMBs applied to hotter thermal environments can only be estimated by projection. The dotted lines in Figure 6-27 show the range of DMB NO_x emissions which can reasonably be expected from the DMB. These lines were drawn to include all DMB data with trends similar to the Foster Wheeler pre-NSPS burner correlations.

This projection indicates that NO_x emissions from the DMB should be less than about 0.4 lb/10^6 Btu even for hot thermal environments. It should be recognized that these projections were based on the DMB performance in research furnaces and at WIPCO under optimum balanced burner conditions. However, balanced conditions were difficult to achieve at WIPCO. Thus, the projections in Figure 6-27 assume that future DMBs can be designed to avoid these problems.

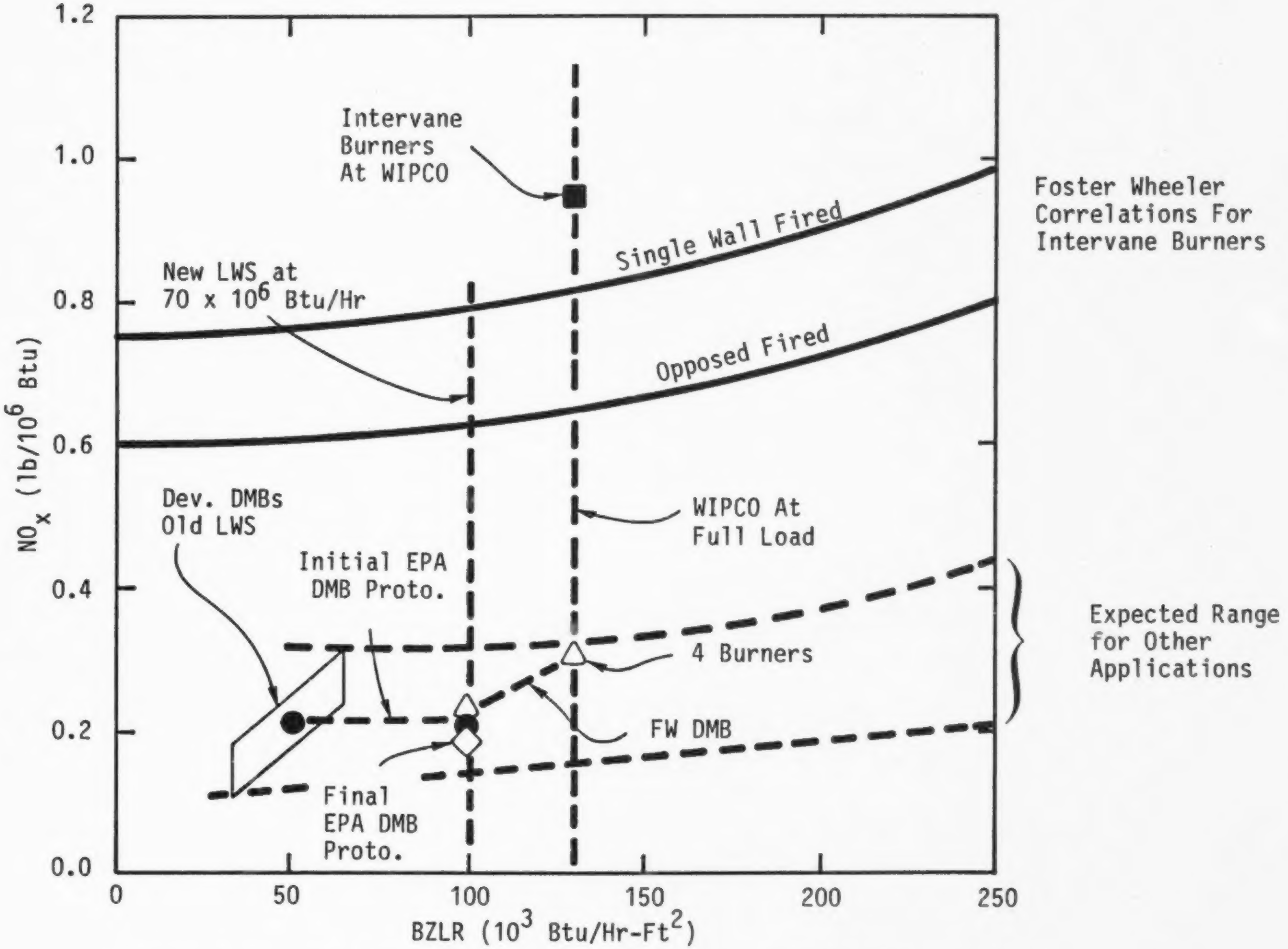


Figure 6-27. Projection of research furnace and field NO_x emission data.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Integration of the DMB Concept with Commercial Burner Components

The DMB concept was integrated with commercial Foster Wheeler burner components designed to meet the requirements of the WIPCO host boiler. This included a commercial coal nozzle, registers, controls and exit geometry from the Foster Wheeler controlled flow burner. The burner design utilizing these components could operate at the DMB design point with acceptable flame shape and stability. A commercial Forney flame scanning and ignition system was utilized with the same locations in the burner as typical Foster Wheeler commercial burners. There were no problems in igniting the flames or verifying flame presence under optimum burner settings. Under some non-optimum burner settings where the basis of the flames were further into the furnace, the flame scanners indicated a loss of flame signal even though stable flames were observed visually. This should not be a problem since best overall performance was achieved with the burners adjusted for short flame stand-off distance. In the event that long flame stand-off distances are required, that the flame scanners may be easily adjusted for satisfactory performance.

DMB Field Installation

The DMB was found to be compatible with the design of the host boiler except for the exit geometry and tertiary air port locations specified in the DMB design criteria. It was necessary to use a much shorter exit than specified by the criteria due to windbox depth and burner-to-burner spacing. However, tests of prototype DMBs with short exits confirmed that DMB performance is not compromised by a short exit design. In fact, best overall performance was achieved with an exit length considerably shorter than specified in the criteria.

The desired tertiary air port array could not be utilized due to the close burner-to-burner spacing and furnace and windbox structural considerations. A compromise array involving thirteen ports with twelve separate controls was selected to provide the most uniform distribution of tertiary air possible. Significant modifications to the burner structure were required to accommodate this array. This included complete replacement of the front wall, relocation of buckstays and windbox trusses and the installation of a special hopper support structure. The compromise tertiary air port array may have contributed to operational problems, especially burner flow balance.

The installation of tertiary air ports on other DMB retrofit installations should be evaluated on a case by case basis. Specific consideration should be given to the locations of buckstays and windbox trusses. Also, for top supported units the adequacy of straight tubes in the front wall to support the hopper should be evaluated.

For new installations it should be possible to design the furnace structure to accommodate the desired tertiary air port array. However, this may involve changes in some furnace design parameters which are usually established by other design constraints including windbox and furnace geometry and the specific burner array.

Parameters Influencing Burner Performance

The key factors influencing burner performance were found to be the specific burner settings influencing burner aerodynamics (such as secondary air swirl), burner zone stoichiometry and burner balance. The burner settings had a significant impact on flame shape, stability and NO_x emissions. Best performance was achieved with settings which produced flames with short stand-off distances. This maximized flame stability and minimized pre-mixing at the base of the flame which contributes to high NO_x emissions. Burner zone stoichiometry influenced NO_x emissions and combustion efficiency. NO_x emissions decreased as burner zone stoichiometry decreased; combustion efficiency decreased sharply at low burner zone stoichiometries. The optimum burner zone stoichiometry depended on burner design and settings but was generally in the range of 70 percent theoretical air for the burner designs tested.

Burner balance is a key parameter for multi-burner installations. Unbalanced air or fuel flows to the burners produce a range of burner zone stoichiometries in a multi-burner array. Those burners with low burner zone stoichiometry have low combustion efficiency. To achieve adequate combustion efficiency, the overall burner zone stoichiometry must be increased. This increases NO_x emissions. Balancing the air and fuel flows supplied to the burners will not necessarily produce balanced flames. In particular, where tertiary air ports are located between closely spaced burners, the tertiary air may be preferentially entrained into one burner resulting in imbalanced flames.

Burner Control

To achieve the optimum burner settings and burner zone stoichiometry with balanced burners requires careful adjustment of the air and fuel flows to all burners. The fuel flow distribution is established by the pulverizer operating parameters and is essentially independent of burner settings. However, in the WIPCO installation, non-uniform adjustment of the coal nozzles has the potential to produce mal-distribution in the fuel flow. The air distribution depends on the burner settings. The WIPCO installation involved a common windbox and as a result a change in any one burner control (such as the register setting on one burner) changed the burner aerodynamics, burner zone stoichiometry and burner balance. The problem could be reduced somewhat by changing the same control on each burner by commensurate amounts. However, due to the significant changes in air flow rates necessary to make a transition from unstaged to staged operation, minor differences in the effectiveness of the burner controls tended to produce burner imbalance. Also, to achieve burner zone stoichiometries near the design point it was necessary to use the maximum restriction settings on all controls affecting the air flow through the burner throats. This made it difficult to adjust burner aerodynamics and burner balance.

Air Flow Measurement Systems

In common windbox installations where the combustion air flow rates supplied to the burner throats and tertiary air ports are not metered separately, the burner zone stoichiometry can be determined only by measuring the air flow rates through each burner passage and tertiary air port separately and summing the results. In the WIPCO installation, this involved measurement of ten tertiary air port flow rates and twelve burner passage flow rates not including the primary air. The design of the internal air flow meters was inadequate to determine burner zone stoichiometry adequately. The major limitation was the design of the air flow meters which involved measurement of the pressure drop across a control device with variable opened area. While these devices were calibrated, there was always some uncertainty in the exact position of the control devices.

Furnace Mixing

The field test data showed that the burner performance under NO_x conditions varied at constant burner settings. Specifically, the distribution of excess O_2 and CO emissions across the boiler width was found to vary substantially with no apparent change in any operating conditions. It is suspected that this may have been due to the compromise tertiary air port array and the resulting entrainment of tertiary air flow from one or more ports into flames from different burners at various times. The most probable port for this unstable operation is the center port since it is surrounded by four burners. Alternate entrainment of the flow from this port into flames on either side of the unit could account for the experimental observations.

Minimum NO_x Emissions

Minimum NO_x emissions of about 0.3 $lb/10^6$ Btu were achieved during several short term tests. This corresponds to a 70 percent reduction from the nominal NO_x emissions with the original equipment Intervane burners of about 1.0 $lb/10^6$ Btu. These low NO_x emissions were achieved for several burner settings which produced short flame stand-off distances, burner zone stoichiometries near 70 percent theoretical air and balanced burners. It was not possible to operate for extended periods with these settings due to three problems: variable burner gas mixing, operator flame shape requirements and possibly slagging. Due to the variable furnace gas mixing, it was necessary to adjust the burner settings often to achieve balanced burners and low burner zone stoichiometry simultaneously. Such adjustment was difficult for the operators whose major responsibility was load following. The operators required that the flame stand-off distances be larger than those commensurate with low NO_x emissions. This was based on previous experience with nozzle over heating. However, thermocouples on the coal nozzles never indicated over heating even for short flame stand-off distances. Excessive ash deposition on the front wall and hopper leading to slagging occurred several times during the testing period necessitating an increase in excess air. It is not clear whether this was due to the burner operating conditions or other potential causes such as poor pulverized coal fineness and variable coal quality which were prevalent throughout the test period.

NO_x Emissions During Extended Operation

NO_x emissions of about 0.5 lb/10^6 Btu were achieved consistently in several extended test periods ranging up to 30 days. This represents a 50 percent reduction from the baseline NO_x emissions with the original equipment Intervane burners. The burner settings used for these tests produced flame shapes generally compatible with operator requirements.

Use of Research Furnace Test Results

The performance of the DMBs in the research furnace was generally similar to the performance measured during the field evaluation. This includes flame stability, effects of burner adjustments and NO_x emission trends. Performance parameters influenced by the design of the furnace downstream of the burner zone (such as CO emissions, ash carbon content and fly ash carryover) were different as expected. Also, since the research furnace test involved single burners only, there was no way to evaluate the impacts of the compromise tertiary air port array used for the field installation. Subsequent isothermal flow modeling confirmed that the tertiary air from a port located between two closely spaced burners may cause imbalanced flames.

Furnace Wall Corrosion

Ultrasonic wall thickness measurements made during the WIPCO demonstration were inconclusive. Corrosion test panels, examined in the laboratory, indicated that there was no metal loss of metallurgical changes due to fireside conditions after 47 months of operation in the Pearl #1 boiler. The test panel method has been found to be the most accurate available and can be considered conclusive evidence that furnace wall corrosion will not be accelerated by DMB application.

Cost

The economic analysis performed for applying the DMB concept to new wall-fired utility boilers indicates that the cost impact can vary significantly. The most significant factor is that of windbox design.

Compared to a conventional NSPS boiler design that incorporates a compartmented windbox, the DMB can be applied quite inexpensively. This is possible if the boiler dimensions remain unchanged by reducing the number of burners, even when applying the DMB design criteria.

Applying the DMB firing system to a boiler design that does not currently utilize a compartmented windbox becomes significantly more expensive.

7.2 Recommendations

DMB Design

Future DMB designs should be based on the DMB design criteria except for the exit geometry. A short exit with a length to diameter ratio of about 0.4 appears to result in improved performance. Any burner components providing the desired velocities and swirl should be adequate. However, research furnace tests to fine tune the design are recommended.

The tertiary air port design for future DMB installations should include an assessment of furnace mixing. If possible, the burners should be widely spaced so that each burner and its surrounding air ports operates independently. If the burners must be spaced closely, there is the potential for flame imbalance due to non-uniform entrainment of tertiary air from shared ports between burners. This was a major problem in this field evaluation. For closely spaced burners and shared tertiary air ports, a flow modeling study should be conducted. Increased tertiary air velocity may be beneficial in reducing flame balancing problems.

Burner Controls

It is recommended that future DMB installations provide for independent adjustment of burner aerodynamics, burner zone stoichiometry and burner balancing. This could be achieved by supplying air to the tertiary air ports from a plenum separate from the windbox supplying the burner throats. If this had been done in the WIPCO installation, the Foster Wheeler burner controls (sliding sleeves and registers, etc) could have been used to adjust burner aerodynamics and burner balance independent of burner zone stoichiometry.

Air Flow Metering

The development of improved air flow metering systems is recommended. Specifically, the air flow meters should be designed for measurement of pressure differentials across fixed restrictions. Overall accuracies of these systems at the burner operating point should be in the range of ± 5 percent or better. However, accuracy is not as important as repeatibility. Flow meters for the same burner passages on different burners must be identical to balance the burners.

Ash Deposition Evaluation

The reasons for excessive ash deposition leading to slagging during some of the WIPCO tests has not been determined but is key to the further application of the DMB. The basic DMB premise is that ash deposition problems are ameliorated by the provision of an oxidizing envelope around each flame via tertiary air injection. Thus, ash particles approaching the furnace walls are in an oxidizing environment which tends to increase the ash fusion temperature. However, these particles are formed under reducing conditions. Therefore, if the tertiary air oxidizing envelope is non-uniform, molten or sticky ash particles in a reducing state may approach and contact the walls. Alternately, if the oxidizing envelope is satisfactory, sticky particles may still impact the walls if the ash particle oxidation and solidification rates are slow. It is recommended that both possibilities be evaluated. The characteristics of the oxidizing envelope could be measured by comprehensive in-furnace probing under low NO_x conditions in a multi-burner array such as the WIPCO DMB installation. Isothermal flow modeling tests could visualize flow patterns as well. A laboratory scale test should be devised to evaluate ash oxidation kinetics and solidification rates.

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